TREBALL FI DE GRAU

Grau en Enginyeria Mecànica

STUDY OF SUPERFICIAL TEXTURES ON CONCAVE PIECES OF ALUMINIUM A2017

Memory-Budged-Annexes

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Resum

El brunyit amb bola és una operació de acabat superficial sense arrencament de ferritja, que consisteix en fer passar una bola aplicant una determinada força contra una superfície. És un mètode molt versàtil que pot actuar en diverses geometries, a més es pot automatitzar en una eina de CAM.

Microscòpicament les superfícies presenten uns pics i uns valls, depenent de la rugositat aquests seran més o menys pronunciats. El procés del brunyit amb bola actua en fred i per deformació plàstica desplaçant els pics a dintre dels valls deixant la superfície més llisa per allà on ha passat i per tant reduint la rugositat. Si s'aplica una vibració entra en joc el fenomen de la electroplasticitat, fet que redueix l'esforç necessari per a la deformació plàstica.

En aquest estudi s'analitzarà la capacitat de la eina de brunyit amb bola en superfícies còncaves de diferents radis, a més es canviaran paràmetres com la força d'aplicació, la qualitat del mecanitzat previ i l'aplicació o no de vibració. Es mesurarà la rugositat en cada una de les marques de brunyit i s'avaluarà el millor procediment per a la execució del brunyit amb bola sobre una superfície còncava, en aquest cas per a peces d'alumini A2017.

Resumen

El bruñido con bola es una operación de acabado superficial sin arranque de viruta, que consiste en hacer pasar una bola aplicando una determinada fuerza contra una superficie. Es un método muy versátil que puede actuar en varias geometrías, además se puede automatizar en una herramienta de CAM.

Microscópicamente las superficies presentan unos picos y unos valles, dependiendo de la rugosidad estos serán más o menos pronunciados. El proceso del bruñido con bola actúa en frío y por deformación plástica desplazando los picos dentro de los valles dejando la superficie más lisa por donde haya pasado y por lo tanto reduciendo la rugosidad. Si se aplica una vibración entra en juego el fenómeno de la electroplasticidad, hecho que reduce el esfuerzo necesario para la deformación plástica.

En este estudio se analizará la capacidad de la herramienta de bruñido con bola en superficies cóncavas de diferentes radios, además se cambiarán parámetros como la fuerza de aplicación, la calidad del mecanizado previo y la aplicación o no de vibración. Se medirá la rugosidad en cada una de las marcas de bruñido y se evaluará el mejor procedimiento para la ejecución del bruñido con bola sobre una superficie cóncava, en este caso para piezas de aluminio A2017.

Abstract

The ball burnishing is a surface finishing operation without chip removal, which consists of passing a ball applying a certain force against a surface. It is a very versatile method that can perform in several geometries, in addition it can be automated in a CAM tool.

Microscopically the surfaces show peaks and valleys, depending on the roughness these will be more or less pronounced. The process of burnishing with ball works in cold and by plastic deformation displacing the peaks inside the valleys leaving a smoother surface where it has passed and therefore reducing the roughness. If a vibration is applied comes in the phenomenon of electroplasticity, fact that reduces the effort necessary for plastic deformation.

In this study, the capacity of the ball burnishing tool is analyzed on concave surfaces of different radius, furthermore parameters such as the force of application, the quality of the previous machining and the application or not of vibration will be changed. The roughness in each of the burnishing marks will be measured and the best procedure for the execution of the ball burnishing on a concave surface will be evaluated , in this case for A2017 aluminium pieces.

Greetings

Thanks to the director of this project Daniel Romanillos for all the time dedicated in the workshop, machining and preparing the CNC mill.

To Carlos Lozano for his advices in the CAM modelling and for providing me the necessary information for the process of data collection.

To my family and friends who, although they haven't actively participated in the project, they have given me moral support. And to my dog Mica who is always happy to see me when I come back home.

Thanks to all.

Glossary

Electroplasticity: Phenomenon that occurs when a determined frequency makes vibrate a piece reducing notoriously the effort needed to deform it. The effect disappears when the frequency goes off without altering the properties of the material after that.

CNC: Computer Numerical Control

CAM: Computer Aided Manufacturing

CAD: Computer Aided Design

Ra: Average roughness of the evaluated profile

Rz Average peak to valley height

Ry: Max local peak to valley height

Rt: Largest peak to valley height.

Rq: Mean square roughness

Cut-Off length: Distance taken to measure some parameter

VABB: Vibration Assisted Ball Burnishing

Lathe: Machine-tool designed to remove material from a piece to end in a final product with symmetry along the revolution axis. In the lathe the piece rotates and the tool stays static.

Milling machine: Machine-tool designed to remove material from a piece. In the milling machine the tool rotates while the piece stays fixed to the bed. The bed can move in the X-Y plane and the tool moves on the Z-Axis but there are types of milling machine in which the tool moves in all the directions and the piece is fixed.

Work in cold: Manipulation of the piece as it can be forging, bending, pressing, etc. without increasing the temperature, leading to a reorganization of the grain making the piece harder but more fragile.

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1. Preface

There is a need to improve the surface quality of the components due to a demand on lowering the friction to reduce the wear and enlarge the life. Enlarging the life of a part implies fewer changes and maintenance. Also reducing the friction will cause a decrease in the energy needed for moving objects in contact which will lead to a cost reduction of the process.

The reduction of the energetic cost in combination with a longer product life have impact on the budged and an adjusted is usually one of the most important requirements in a project.

1.1. Origin of work

There has been different tests in flat surfaces and in different materials as aluminium, steel or titanium. In those scenarios the application has been performed without any significant issue, although the results were different depending of the parameters in each case, at the end all of the projects have achieved some reasonable conclusions.

All those projects had different peculiarities but all of them have shared the same flat geometry. To check the versatility of this process now the surface gets changed to a concave form in three different radius to see how the burnishing process works and how the tool behaves under this conditions.

1.2. Motivation

To continue with a previous investigation line in the field of the ball burnishing made by the mechanical engineering department this semester it has been presented this project as a finishing grade project to advance in the research process about this particular surface treatment procedure.

1.3. Previous requirements

For the correct understanding of this article, although it will be explained to be understood by everyone, the reader will find it easier if it is familiarized with the field of the manufacturing processes and has knowledge in materials engineering, also concepts such as compression stress, fatigue, and other engineering terms will appear.

The process has been automated but there is no need to be an expert or to have notions in CNC since this part is only important if it is wanted to repeat the project. It has not much effect in the final result. The final conclusions, which is the point of the essay, are completely understandable without having to manufacture the piece.

2. Introduction

2.1. Objective

The principal goal is to analyze the surface after a ball burnishing in concave geometries. There will be made various burnishing footprints in order to change the execution parameters and observe the differences that those variations have done.

In the beginning it has to be manufactured the piece from a block of raw material, then proceed to the burnishing and finally measure the results in two different rugosimeters, an optic one and a contact one.

Finally the results must be compared between the two types of rugosimeters and reason the meaning of those. Also the results among footprints must be compared and analyzed, then arrive to a conclusion of which combination is the best.

2.2. Scope

Due to a limitation of time and resources the project will only be treated the field of the surface quality, leaving without taking into account the fatigue life or the increased hardness, due to a work in cold, left for another study as happens with the residual tensions on the surface from the compression.

The fatigue life is related with the residual compression tensions which help to not to propagate the scratches in a cycle of work. The incremented hardness is only found on the surface when a compression effort is done but in the majority of cases that is what is needed, hard on the outside and soft in the inside to resist the wear and absorb the blows, but that is something already known, the reason why this aspects are left aside.

2.3. Previous concepts

2.3.1. Machining with chip removal

For the manufacturing of many pieces one of the most common ways is to start from a block of raw material and from there begin removing material that comes in form of chip. That procedure is known as machining with chip removal.

The chip removal is done with different machine-tools like the lathe or the milling machine. The principal advantage of this manufacturing method is the excellent precision, reaching really good levels of tolerances, in the level of microns. It also lets a big diversity of geometries.

The machining is defined by three characteristics moves: Cutting move or principal move, advance move and feeding move.

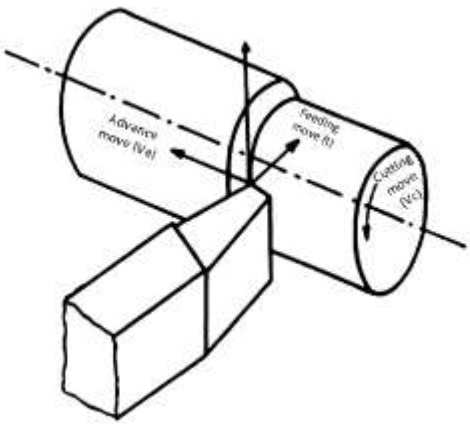


Image 1. Principal moves and its associated parameters

The cutting move is the move that lets the tool penetrate into the material, it's governed by the cutting speed parameter (Vc). This is the relative speed between the piece and the tool, it depends on the spindle speed and the diameter of the tool or the piece, depending which one is rotating. If the machine is a lathe the piece will be rotating and it's diameter will be the one that influences the cutting speed. If the machine is a milling machine what rotates is the tool and its diameter will determine the cutting speed.

The advance move is the movement that allows the tool a displacement while cutting letting the tool cut through the piece continuously. Feed rate (Va) is the parameter that governs it and it influences in the cutting time.

The feeding move, lets the tool cut a determined thickness of material, it is governed by the depth (t) parameter.

This three parameters can be combined in many different ways in order to create different surface qualities.

2.3.2. Surface quality or rugosity

When seen macroscopically a surface can look rough or smooth. To quantify that roughness or smoothness exists the rugosity or surface roughness, which gives numerical value for that roughness. It is measured in µm, the lower the value of that rugosity the better will be the surface.

It is called a good quality surface when there is low rugosity but it doesn't mean that low rugosity is always good. In some cases what is wanted is a poor surface finish, that is, a high value of rugosity. For example if there is a need for a grip because that piece is going to be hold, twist, etc. by a person, a good surface quality is not the target, in that case a bad surface quality is the objective.

This surface quality depends from the previous type of machinig operation performed. The combination of the cutting parameters (Vc, Va and t) make a determined surface and has to be controlled to save time while having a minimum quality. For a better surface, the operation is called finishing, that impies high cutting speed and slow feed rate, it is a slow process and has to be done after the roughing so as not to make the surface worse. The roughing pretends to remove the maximum material in the less time possible, it leaves a bad surface, for that, the cutting speed is slow and the feed rate is fast, this operation saves the integrity of the tool by making the cutting speed slow and saves time by makin the feed rate fast.

If looked microscopically the profile looks like this:

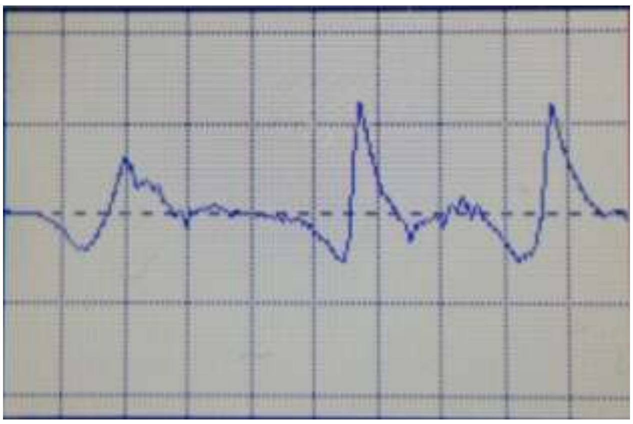


Image 2. Profile of the rugosity

The peaks and valleys correspond to the path of the tool, if the blade advances fast (high feed rate) the peaks will be separated, and if the cutting speed is slow every time the blade cuts it has travelled a certain distance making the peaks far one from the other also if the depth is elevated the peaks will appear higher.

On the opposite side if the cutting speed is high the cutting edges are more frequently removing material and making the peaks closer one from the another, if the feed rate is slow the tool will have time to cut every few microns and the peaks will overlap making the distance peak-valley smaller, this combined to a smaller feed gives small peaks and valleys and with that a smoother surface.

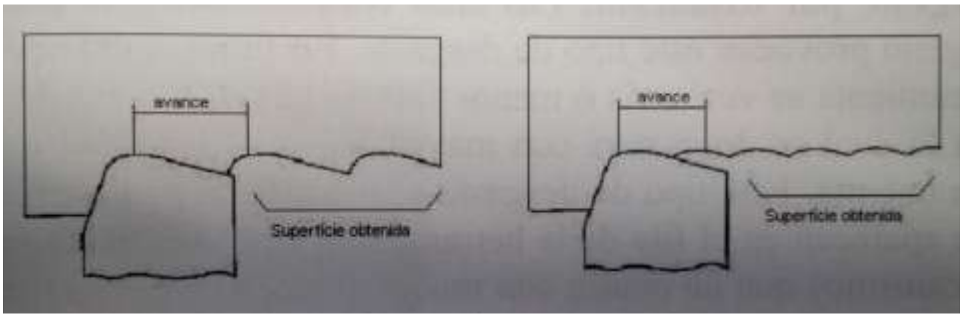


Image 3. Influence of the cutting parameters. Source[1]

Although this surface has a strong limitation due to time, to reduce it exists the possibility of reducing the surface roughness by the ball burnishing process in less time.

2.4. Ball Burnishing

The ball burnishing is a non chip removing process to enhance the surface quality. It works in cold by plastic deformation. A ball is pressed against the surface and it is made roll over the surface. On its way it leaves a smoother surface because it deforms the imperfections. It will be clearer taking a look at **Image 4**

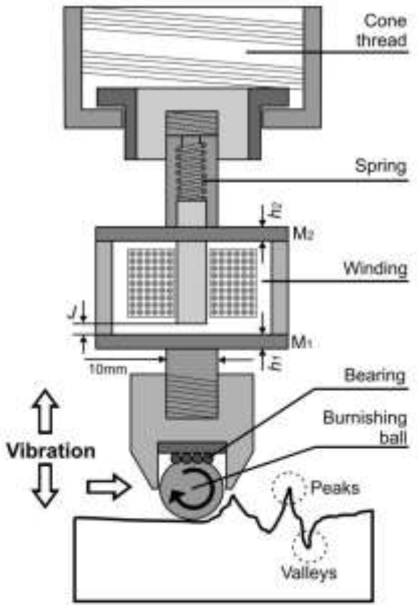


Image 4. Scheme of the ball burnishing tool and its working [2]

The ball glides and presses the peaks against the valleys by plastic deformation flattening the peaks and filling the valleys, reducing the height of the imperfections. As it is a work in cold has the benefits of it. It gives an increase on hardness on the surface and leaves residual compression stress that helps to enlarge a fatigue life, also a good surface quality helps the fatigue life. A good surface finish helps not to start a crack and residual compression helps not to expand the crack.

In case of relative movement the increased hardness on the surface prevents premature wear and it is combined with a higher surface quality that reduces the friction coefficient reducing the wear and the energy loss. Then the wear is reduced by two sides, making the material more resistant and preventing it.

Image 5. Ball burnishing tool

Image 6. Details of the ball burnishing tool

2.4.1. Vibration Assisted Ball Burnishing (VABB)

The burnishing tool has been has been upgraded with vibration in order to improve the results. A vibration in the ball is transmitted to the material and then appears a phenomenon called electroplasticity. The electroplasticity helps to reduce the effort needed to deform a material and as the ball burnishing works by plastic deformation it is very useful for the appliance. It reduces the effort or with the same effort makes a greater deformation, the electroplastic effects disappear immediately after the vibration goes off.

This coupling of a vibration to the tool has been designed by Mateu [3] and experimented by Gomez [4]. It is attached a frequency generator to a coil that is mounted inside the tool, this coil produces a magnetic field that induces a vibration to the ball.

Image 7. Frequency generator

The red button "test" was the first button to set on and off the vibration but to use it for burnishing, that have to be on during the time it is working it was more comfortable to change the switch to the one shown below, that is on or off until it is changed.

Image 8. Detail of the switch

Image 9. Detail of the connexion with the tool

The vibration in the machine is set at 100% of its intensity because in other tests have been proved that there is not much difference, with this the frequency is 39kHz, at sight it can't be seen if the vibration is on or off but putting a finger in the ball it is noticeable a little vibration. When in use to check if the ball is vibrating or not the "US" light indicates it, if it is on the light is on too, if the vibration is off then the light is off too.

3. Experimental method

This project has a very heavy experimental component, it's not only a theoretical paper, there has been a need to perform tests, obtain results, compare them and reason the results.

It hasn't been only a research study by collecting information from other authors, the study was done by essay and fail making it longer and having to be present every time a test had to be performed.

Errors occurred, but they have had a correct solution and at the end logic conclusions have been found. The paper will follow the chronological order of the experiments, showing first the approach of first experiment until the moment it failed and it is discarded.

Then it will be shown the same procedure but with the adequate corrections to ensure reliable results and it will be explained why the results on the first test where unsatisfactory.

After this it will follow the measuring with both rugosimeters and the analysis process.

3.1. Test 1

The first test finishes after the burnishes, which are unsatisfactory, it will be explained why, but the first steps were correct.

3.1.1. Piece design

The mechanical engineering department facilitated the specification of the wanted piece and then it has been designed. The planes will appear in this document on the annex section.

It is important to ensure that there are no collisions with the tool and the piece in a CAM process, it is a problem that can lead to the breaking of the tool, the piece or the machine, so that's why it's better to check for collisions although the CAM softwares usually include a function for that.

For the burnishing there was danger for the tool cap to intersect with the crest of the curve, above all, the most worrying was the smallest one, for the 80mm radius, because for a god measuring the footprints must be as big as possible, and there had to be determined which was the biggest surface that was able to be burnished without collision, if the footprint were too close to the edge the tool would hit the piece.

To avoid that there has been made a 3D simulation of the piece and the tool to check for the collisions and correct the size of the footprint.

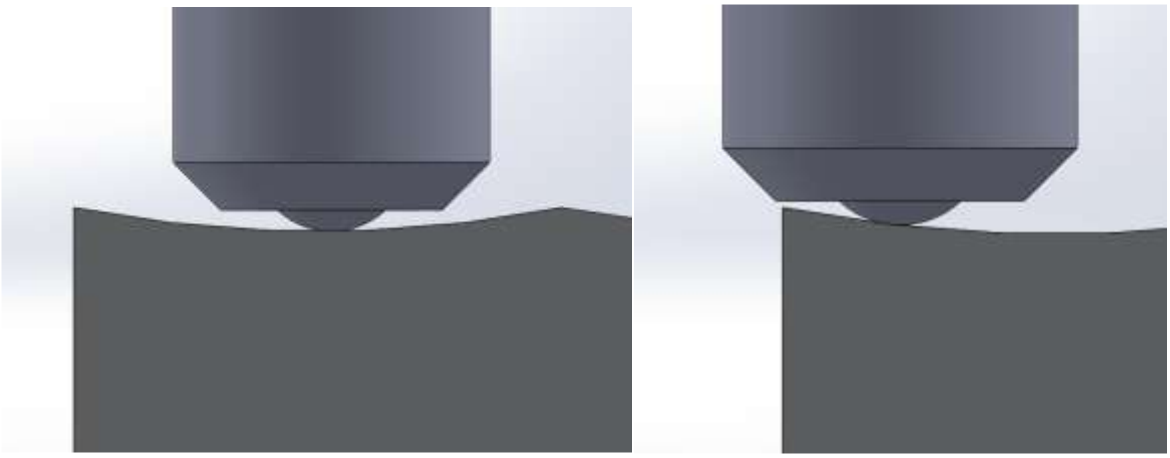


Image 10. Collission simulation

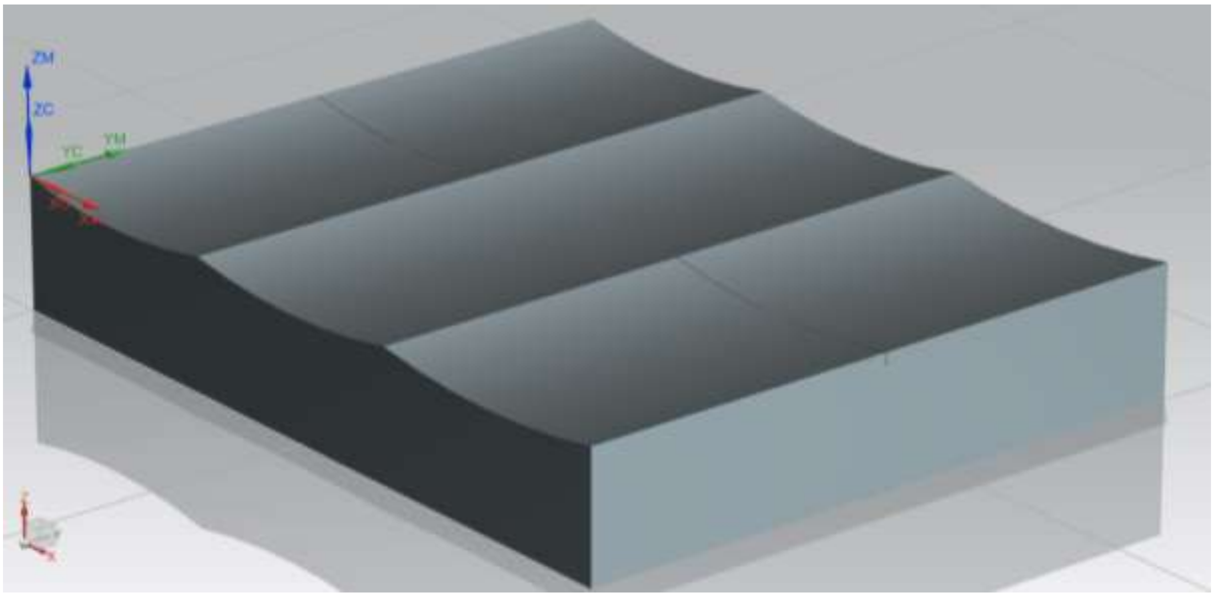


Image 11. 3D design of the piece

3.1.2. Experiment design

The first step on this project was to design which were going to be the parameters combination to take into account at the time of performing the essay on the workshop. At first the force applied, the previous surface quality left by the machining, the curvature radius, the strategy and the appliance of vibration or not where the variables of this experiment.

The forces selected were 180N, 215N and 250, the previous surface quality was set at a crest height of 0,1mm, 0,02mm and 0,06mm, the curvature radius of the piece, 80mm, 90mm and 100mm, and finally the last variable was the burnishing strategy, making the burnishing parallel to the machining, perpendicular or oblique at 45º

With all that parameters there had to be made the combinations.

It was decided that the central area would have the same parameters for every footprint, 90mm curvature of the central area, 45º from the previous machining, 215N and 0,06mm of crest high, the only thing that changes is the vibrations, that is applied on half of the burnished surfaces as happens with the rest of the piece, so the left combinations for the other two zones were:

Strategy: Parallel or perpendicular. (From here it will be abbreviated as // or |- respectively)

Force: 180N or 215N

Radius: 80mm or 100mm

Previous machining crest height: 0,02mm and 0,1mm

With that there were 2 possible ways of using 4 variables, then the total experiments must follow combination with repetition formula, being *n* the possible number of values that can take the variables and *m* the number of variables:

$$Total\ experiments = n^m \qquad \textbf{(Eq. 3.1)}$$

n=2 Values that the variables can take

m=4 Number of different variables

$$Total\ experiments = 2^4 = 16 \qquad \textbf{(Eq. 3.2)}$$

So there had to be 16 different burnishing footprints without having into account the central zone, those 16 experiment had a concrete parameter combination that is being presented below schematically for an easier understanding and are numbered to identify each one:

nº	R	Strategy	h	F
1	80	//	0.02	180
2	80	//	0.02	250
3	80	//	0.10	180
4	80	//	0.10	250
5	80	|--	0.02	180
6	80	|--	0.02	250
7	80	|--	0.10	180
8	80	|--	0.10	250
9	100	//	0.02	180
10	100	//	0.02	250
11	100	//	0.10	180
12	100	//	0.10	250
13	100	|--	0.02	180
14	100	|--	0.02	250
15	100	|--	0.10	180
16	100	|--	0.10	250

Table 1. Parameter combination for every burnishing footprint without vibration

Once finished the non assisted ball burnishes (NVABB) it had to be repeated everything for the vibration assisted ball burnishing (VABB) so at this point there would be 32 burnishing footprints.

Now the schema must follow the same aspect as the previous table (Table 1) and to not be redundant it won't be shown below , the only difference is that now the burnishing footprints have been assisted with vibration and the table.

It could have appeared all together in the table 1 if in the equation Eq. 2 it would have been taken into account the vibration on or off as a variable, in that way the equation should be:

$$Total\ experiments = 2^5 = 32 \quad \textbf{(Eq. 3.3)}$$

This way the result is the same but it has been wanted to reinforce the idea that half of the burnishes had been performed with vibration and the other half without it.

Now it would only be left the central area, that has only one possible permutation for every variable, it happens the same as with the other zones, half of the marks have to be done with vibration and half without it. As it has been said before in this paper the parameters are:

nº	R	Strategy	h_c	F
18-22	90	45º	0.06	215

These essays have to be performed 4 times for the NVABB and another 4 times for the VABB. So on the totality of the surface of the piece there have to be 40 burnishing footprints. Coming up next is shown a table to order the numbered combinations.

<table>
<tr><td>15</td><td>16</td><td colspan="2" rowspan="2">No burnished zone</td><td>40</td><td>37</td></tr>
<tr><td>14</td><td>13</td><td>39</td><td>38</td></tr>
<tr><td>12</td><td>11</td><td>18</td><td>17</td><td>33</td><td>36</td></tr>
<tr><td>9</td><td>10</td><td>19</td><td>20</td><td>34</td><td>35</td></tr>
<tr><td>8</td><td>7</td><td>22</td><td>21</td><td>29</td><td>32</td></tr>
<tr><td>5</td><td>6</td><td>23</td><td>24</td><td>30</td><td>31</td></tr>
<tr><td>3</td><td>4</td><td colspan="2" rowspan="2">No burnished zone</td><td>25</td><td>28</td></tr>
<tr><td>2</td><td>1</td><td>26</td><td>27</td></tr>
<tr><td colspan="2">R80</td><td colspan="2">R90</td><td colspan="2">R100</td></tr>
</table>

Table 2. Burnishing order for test 1.5

As there are many different zones with different burnishing footprints on it every zone is being numbered to take reference, the difference among zones is the previous machined surface quality and the curve radius. In the picture it is shown clearly:

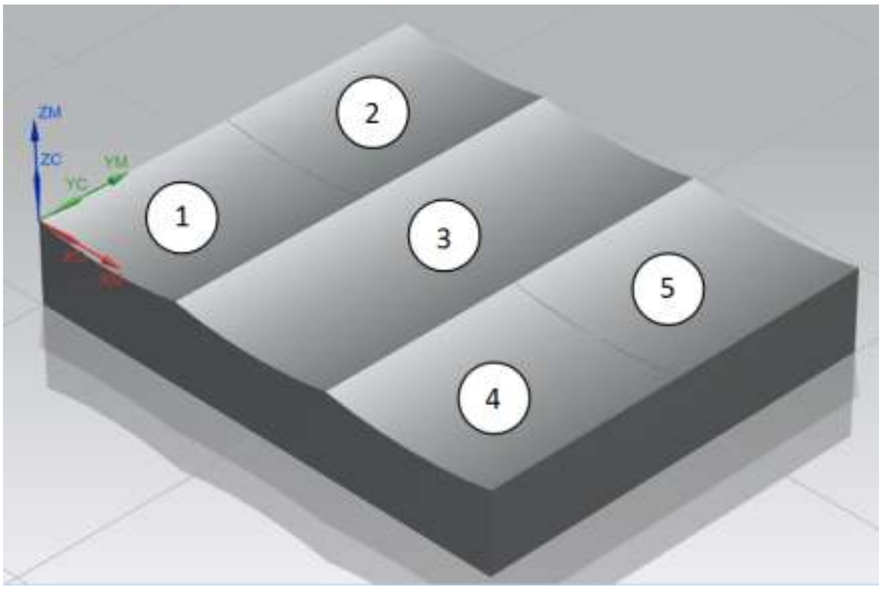


Image 12. Zone identification.

3.1.3. Piece manufacturing

The objective is to analyze the surface after the burnishing on a concave surface, and to perform the burnishing the piece already needs a concave geometry, for that it has to be processed.

In the workshop there was a block of raw material of aluminium A2017. That block had to be machined on the CNC milling machine. For that a CAM program was needed. It was used the previously 3D CAD desing and with that it could have been done the program for the roughing and for the finishing of every surface.

The software used was Siemens NX 11.0. It has been perrformed first the rouguing for all the piece to end in a geometry with three concavities and after that the finishing to preadjust the surface as its required for the burnishings. As shown below in the following images the lines are the path followed by the tool. In this case the tool has been a 8mm diameter spherical mill.

Image 13. Detail of the spherical mill

The tool is attached to a tool holder and this to the machine by a pneumatic system

Image 14. Tool mounted into the machine

The parameters for every operation as well as the time used will be shown below as a table for an easier comprehension:

Operation	Spindle speed (rpm)	Feed rate (mm/min)	Step (mm)	Time (h:min:s)
Roughing	1800	250	1.3	00:24:28
Finishing (zones 1 & 4)	2500	150	0.715	00:13:05 zone 1 00:14:23 zone 4
Finishing (zone 3)	2500	150	1.29	00:18:11
Finishing (zones 2 & 5)	2500	150	1.6	00:6:08 zone 2 00:7:22 zone 5
			Total	1:23:49

Table 3. Cutting conditions

And the simulation of the path followed by the tool is shown in this images:

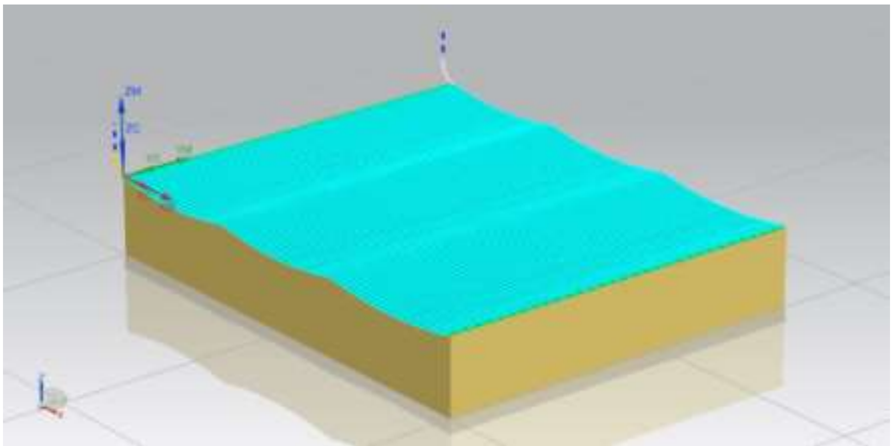


Image 15. Tool path for the roughing of all the piece

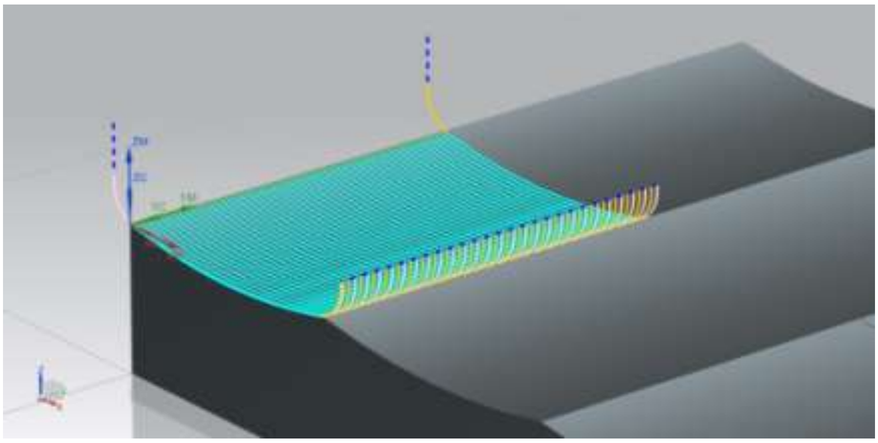


Image 16. Tool path for the finishing to end in a h_c=0,02mm (Zones 1 and 4).

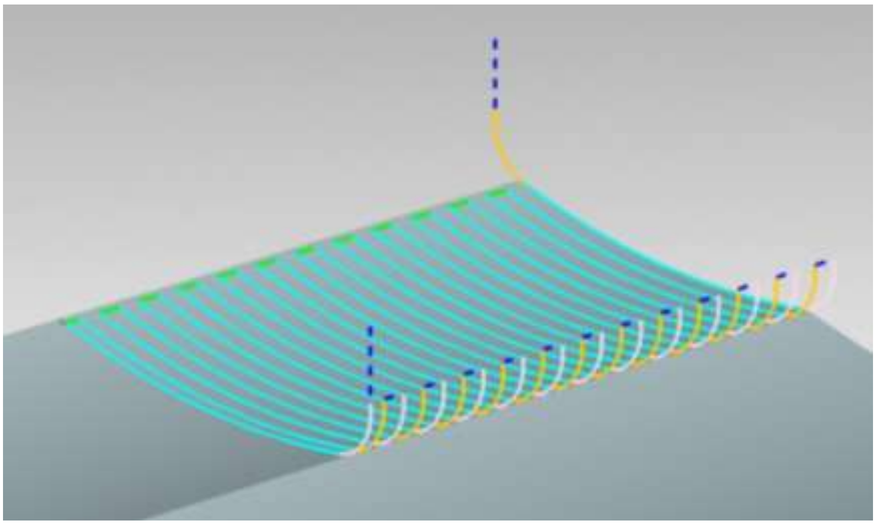


Image 17. Tool path for the finishing to end in a h_c=0,1mm (Zones 2 and 5).

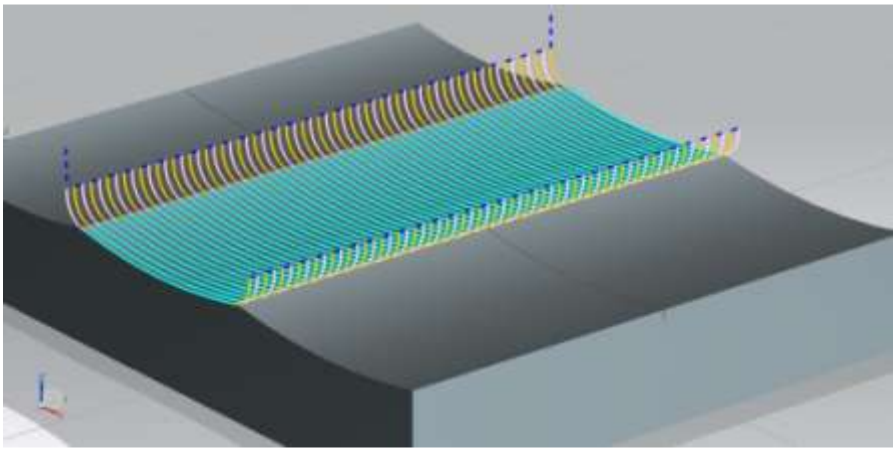


Image 18. Tool path for the finishing to end in a h_c=0,06mm (Zone 3)

After the machining the piece can't be removed from the machine because the origin wold be lost

Image 19. Real piece afther the machining, still in the claws to not lose the reference.

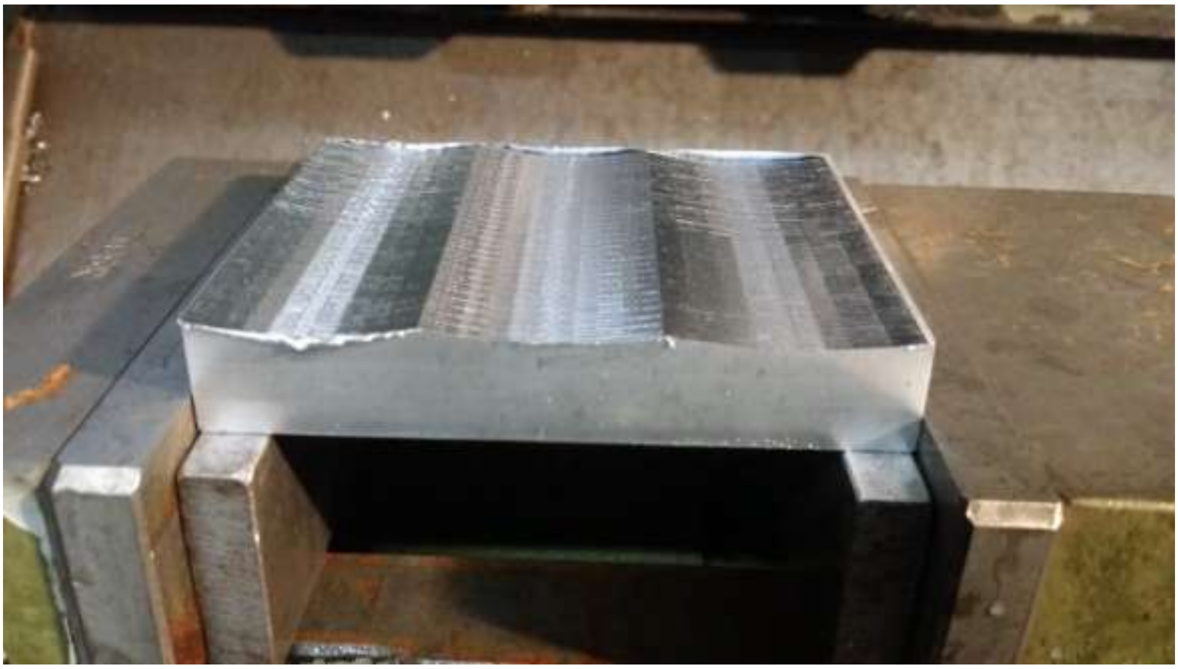


Image 20. Image of the piece afther the machining, still in the claws to not lose the reference (2)

3.1.4. Burnishes

For the burnishes the same procedure was applied as for the machining, a CAM program using Siemens NX 11.0. On the burnishes what changes from the machining is that spindle speed must be 0 rpm because the burnishing tool doesn't rotate, it only glides through the surface. If it would rotate it would rip off the cable that is connected to the wave generator for the vibration.

For the specified force the tool has to go down and press against the surface. For the forces selected these are its associated depths:

Force (N)	Depth (mm)
250	1.4
215	1.15
180	0.9

Table 4. Correspondence of the penetration with the force applied

For the limitation due to collision the footprints were set to 5x5mm and the distributions is shown in the image below:

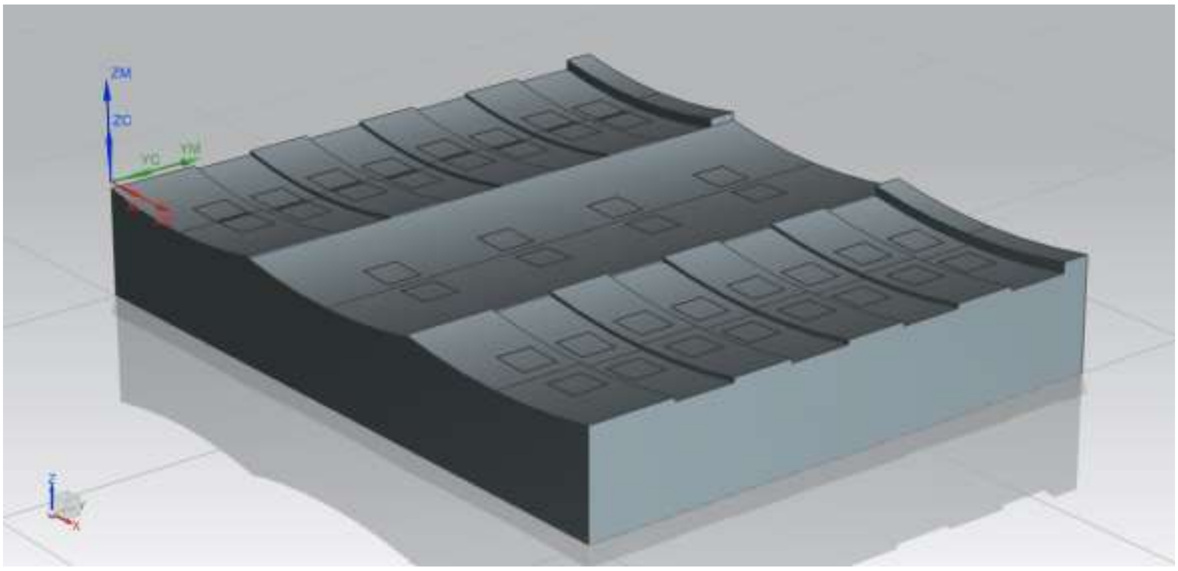


Image 21. 3D CAD to create the burnishing CAM program

To make the squares, the previous 3D CAD used for the machining had to be changed as well as for the correct force appliance. To make the squares a cut was made and the surface was edited and made lower. It can be seen that the surface is staggered, every heigh corresponds to a force, being the higher surface for the lowest forces and the lower surfaces to the higher forces.

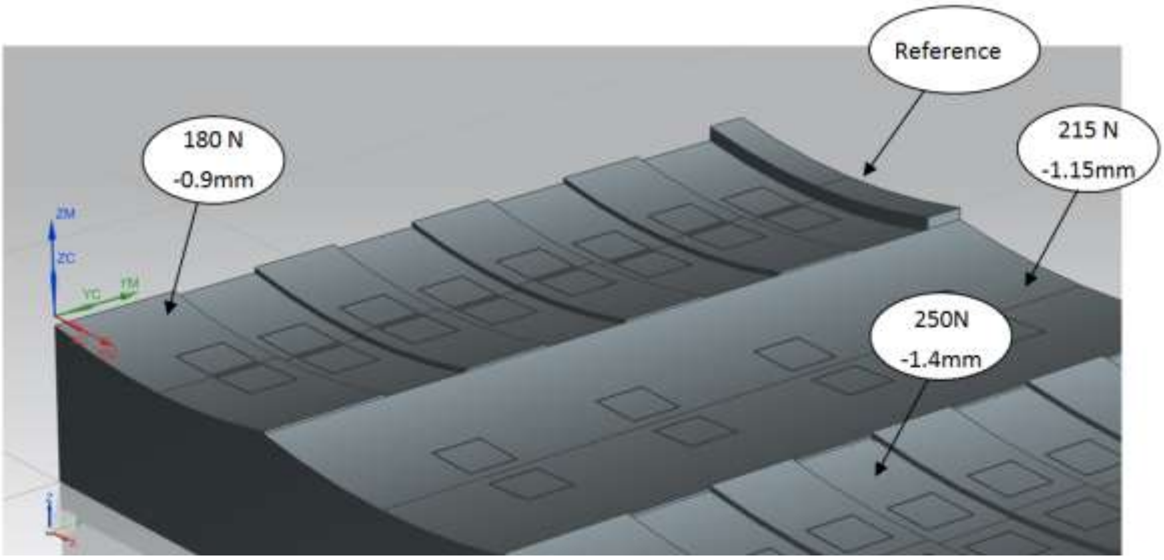


Image 22. Annotation the forces and its depths for the CAM

What it says reference

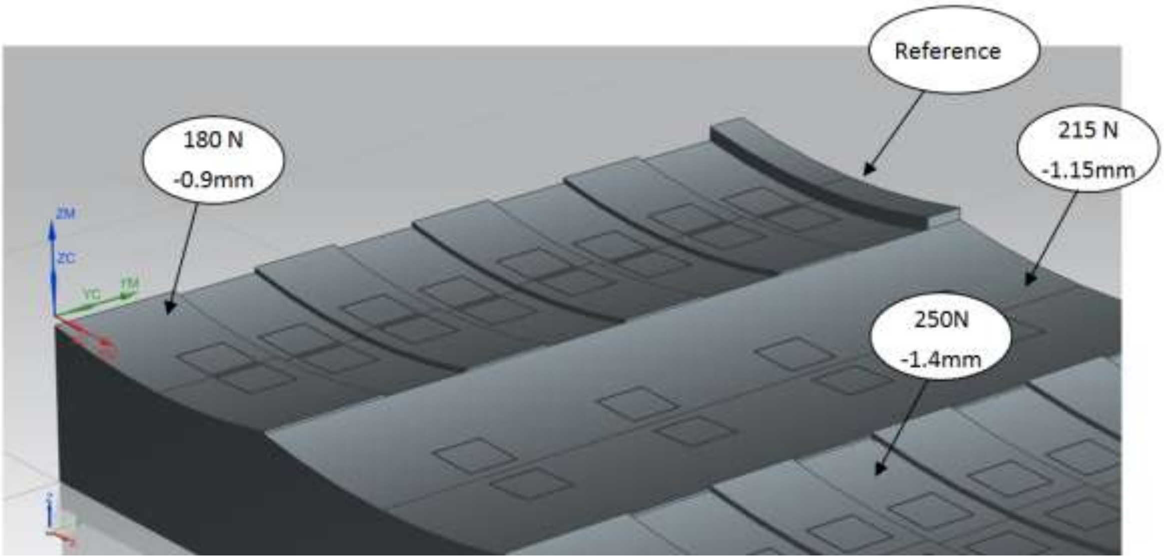


Image 22 is the original height of the machined surface, not the origin of the piece. The origin is the three axis in blue, green and red.

Having this all that was left was to go to the workshop and do the experiments, unfortunately it went everything as good as it was expected. The following pictures are from the real piece:

Image 23. Real piece after the burnishings

Image 24. Failed burnishings

It can be seen that the burnish marks are not squares and are too small, with this the measure can't be performed with guarantee of true results. The reason why this marks are not successfully is the combination of small burnishing surfaces (5x5mm) and applied forces too strong. While performing the experiment it could be seen that the tool got stuck and didn't glide correctly, and when the ball started rolling it only did it for a few millimetres because it had finished the surface to burnish.

The burnishes looked shiny but it needed to be done in a bigger surface so measures could be taken correctly, that's why there are no measures in test 1. What came after this was the needed changes and the start of the 2nd test.

3.2. Test 2

The piece is the same so there is no need to make any changes in this aspect, what it needs to be changed is the experiment and with that comes another changes.

3.2.1. Experiment design

Bigger surfaces are needed for sure and, to make sure the tool doesn't get stuck, the forces are lowered .

The change in the force has been set in a 1mm less of depth except for teh 180N that has associated a depth of 0.9mm but in this time is left as the bigger force, being the other two forces 129N (0.15mm) and 153N (0.4mm). The 215N passes to 129N and the 250N now it will be 153N.

The strategy variable gets suppressed and the burnishings will only be performed perpendicular to the crest. This changes the previous experiment design a little. Now the amount of different variables is 3 instead of 4. So when applying the equation Eq. 3.2 the result now is:

$$Total\ experiments = 2^3 = 8 \quad \textbf{(Eq. 3.4)}$$

With vibration a total of 16 experiments in the lateral zones and taking into account the central zone that had the same parameters for every footprint it will have 4 essays 2 assisted with vibration and 2 without it to make a total of 20 burnishes.

Now that there are only 20 burnish surfaces there is more space on the surface so it could be performed every experiment per duplicate for a better statistic results but as one of the needed corrections is to get a bigger burnish surface instead of making two burnishings, that two burnishes with the exact parameters will fuse into one big burnishing surface and the measure will be able to be made on a larger line and thus more accurately.

As it has been deleted the strategy variable all the burnishings will be performed against the crest, which means, perpendicular to the mill's path.

The order is set in the following way:

8	12	13
7		14
6	11	15
5		16
4	10	17
3		18
2	9	19
1		20

Table 5. Burnishing order of the 2nd test

This reference is used to identify every burnish footprint, to every one of those there is a parameter combination associated, the next list shows what parameters correspond to its number.

nº	R	h_c	F	Vibration
1	80	0.02	180	NO
2	80	0.02	153	NO
3	80	0.02	180	YES
4	80	0.02	153	YES
5	80	0.10	180	NO
6	80	0.10	153	NO
7	80	0.10	180	YES
8	80	0.10	153	YES

Table 6. New parameters for the R=80

nº	R	h_c	F	Vibration
13	100	0.10	180	YES
14	100	0.10	153	YES
15	100	0.10	180	NO
16	100	0.10	153	NO
17	100	0.02	180	YES
18	100	0.02	153	YES
19	100	0.02	180	NO
20	100	0.02	153	NO

Table 7. New parameters for the R=100

And for the central area:

nº	R	h_c	F	Vibration
9	90	0.06	129	NO
10	90	0.06	129	NO
11	90	0.06	129	YES
12	90	0.06	129	YES

Table 8. New parameters for the R=90

Being the 9 exactly as 10 and 11 as 12. This is not a problem, when measuring there will be more data and the results will be more accurate.

In this second test the burnishings have the following look:

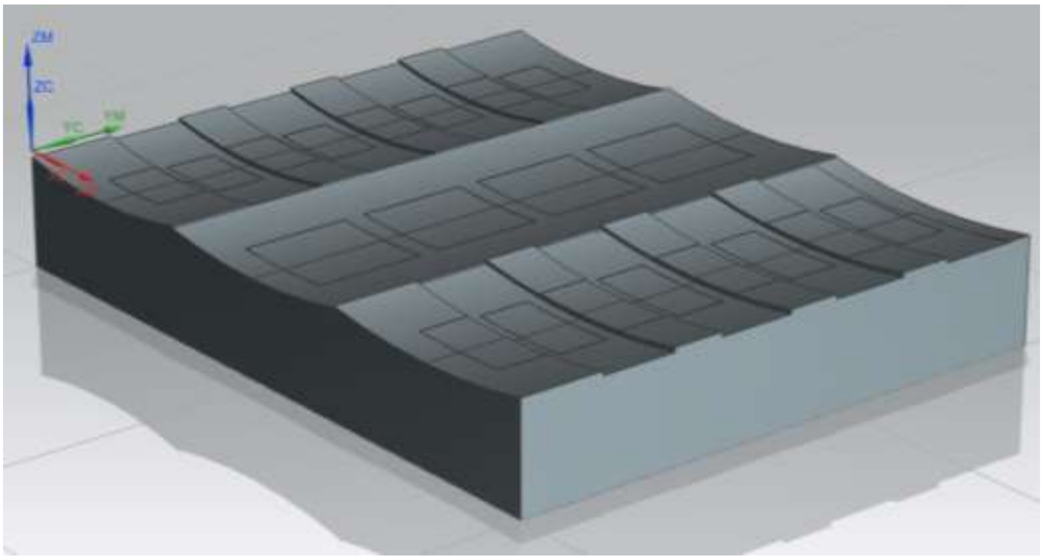


Image 25. 2nd burnishes surface

It can be seen that the steps are not as big as were in the first test because of the lowering on the forces.

The burnishes in the 80mm radius are 11x7mm, the ones form the 90mm radius are 15x15mm and the ones from the 100mm radius are 15x7mm

3.2.2. Piece manufacturing

The manufacturing is the same from the first test, but to not waste the material from the first test it has been machined again. First made a facing to have a flat surface again and then executing the same program. There is one thing that has to be taken into account which is that the reference is lower, depending of the depth of the facing, and the CNC has to be prepared with that new origin.

The time and the parameters are exactly the same as in **Table 3** and for that reason it won't appear again.

3.2.3. Burnishes

The burnishings have had the same procedure as in test 1. As shown on

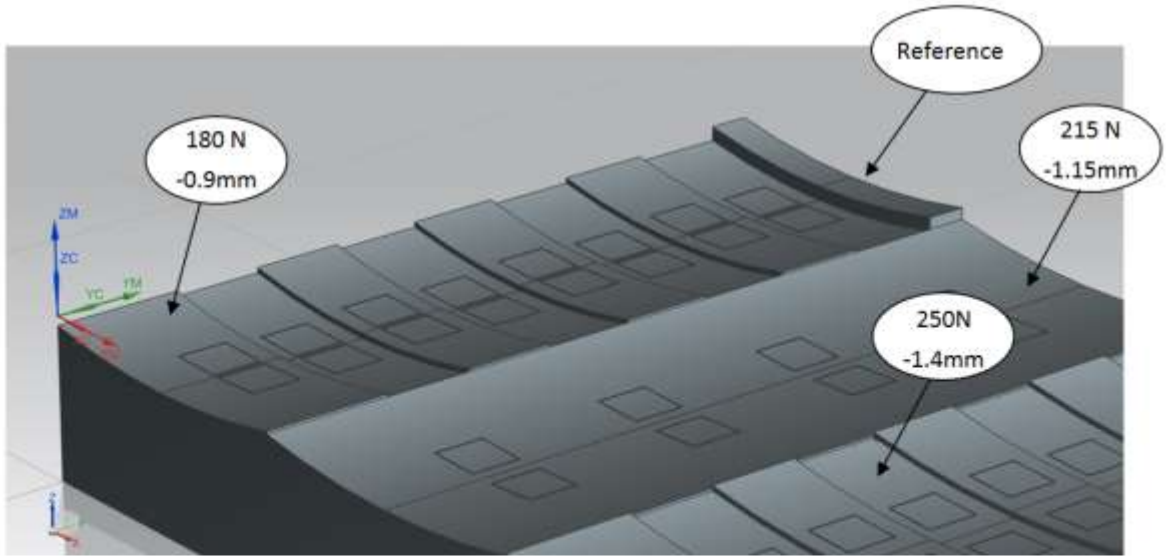


Image 22, every different force correspond to a different depth but now with the following relation:

Force (N)	Depth (mm)
180	0.9
153	0.4
129	0.15

Table 9. Association of burnishing forces with its characteristic depth

The burnishings follow the next pattern:

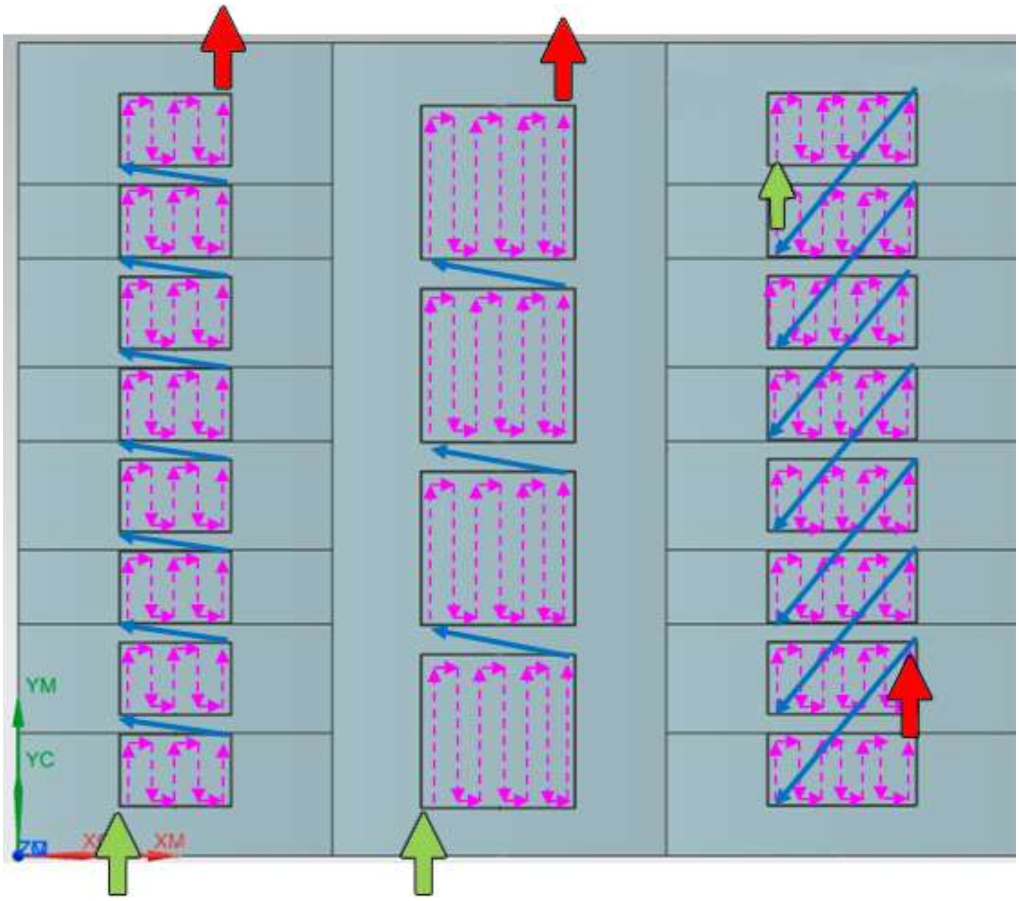


Image 26. Path followed thy the burnishing tool

The burnishings have been separated in three different programs, named R80, R90 and R100, one for each concavity and will be executed one after the other. In the **Image 26** the green arrows are the entrance of the tool, the pink ones are the path that follows while burnishing, the blue are the trajectories without working, finally the red arrows are the exit of the tool and the end of the program.

Every time it finishes one program the next one can be loaded and executed. After executing the process in the CNC milling machine the result is shown in the pictures below:

Image27. Burnishings after the 2nd test.

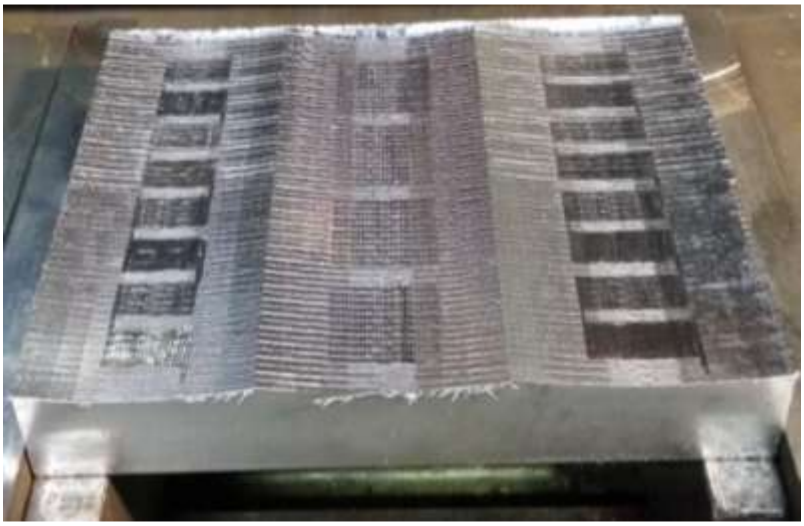


Image 28. Burnishings after the 2nd test (2)

It can be seen that the burnishes are more defined and precise, although in the central zone with the lowest forces it's not as easy to differentiate the burnished area from the machined. This states that there is a minimum force needed for a successfully burnish, the ideal will be discussed in the data comparison section.

The burnishing is quite faster than the machining. The parameters for the burnishing as it has been done with the machining are shown in the next table:

Program	Feed rate (mm/min)	Step (mm)	Time (min:s)
R80	600	0.25	4:14
R90	600	0.25	6:05
R100	600	0.25	5:37
		Total	16:09

Table 10. Burnishing conditions

The conditions in **Table 10** are the same that have been used in the burnishings for test 1. In that occasion there were many different programs due to the change of the strategy and as in the end it have been useless there is no need for a long description, what is has to be said is that in total, the burnishings from test 1 lasted 19min 37s.

Comparing both tests the difference can be a result of all the non cutting moves. With a moderate feed rate like in this experiment, not lifting the tool optimizes the process time. So if it's indifferent to burnish or not to burnish an intermediate surface it can be burnished to safe time. If the burnish was very slow the thing would change and the non cutting moves would safe time but this is not the case.

In any case the burnishing is faster than the machining lasting around a **80% less time,** that means that the burnishing takes only the 20% of time of the machining.

3.2.4. Measuring

The measures have been performed in two different machines. One is a contact rugosimeter, the Mitutoyo Surftest SJ-210, and the other is an optic perfilometer, the STIL Micromesure 2.

3.2.4.1. Contact measures

The first measures have been caught with the Mitutoyo Surftest SJ-210. This rugosimeter analyzes the profile in a line by making contact with the surface and moving in solidarity catching the peaks and the valleys, later the machine processes the data obtained and translates it into the rugosity measuring variables Ra, Rq, Rt and Rz.

The machine catches the profile by retracting a pivot that is articulated like a turntable needle.

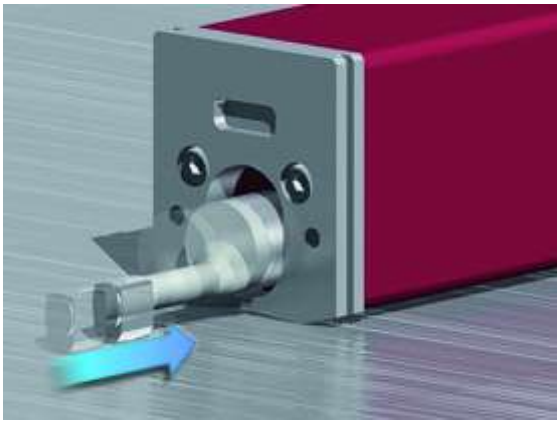


Image 29. Movement of the pivot.

Also as said it can be lifted from the base to not hit the tip that is a made of diamond and is fragile. The tip is also damped very softly, and with a minimum contact it goes up, it's in the tip that the profile is recorded, that's why its so soft, so it can catch all the profile. Also if it wasn't soft it would scratch the surface after measuring.

At first there was risc of scratching the surface but due to schedule the measures couldn't be done first with the optic profilometer. If there would be scratches then it had to be taken into account and avoided at the time of using the other machine. Luckily not any mark of the contact measuring has been found in the second measuring.

Image 30. Calibration of the rugosimeter

To take the measures the first is to calibrate the machine with a standard reference.

Image 31. Detail of the Mitutottyo's standard reference

After the calibration it can be started to measure. It has been decided that the measures have to be made against the crest of the burnishings, that is, perpendicular to the burnishing tool path, in other words, the pivot has to move parallel to the machining. Determining this affect on the second measuring because the value of rugosity varies with the direction of measure having a higher rugosity against the peak and a lower rugosity parallel to it, but it's more difficult to make a measure parallel to the burnishing valley because the machine has to be very aligned.

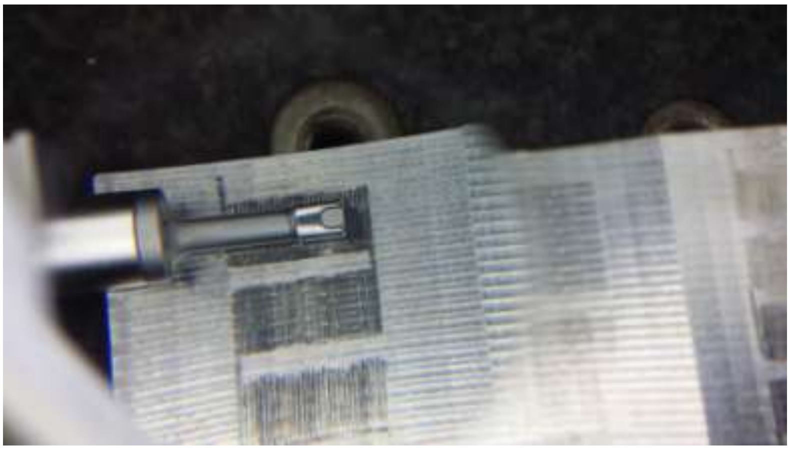


Image 32. Detail of the alignment of the measure, perpendicular to the burnish.

Image 33. Detail of the measure on front view.

As shows the **Image 33** the pivot has a block on it's point. It have been to avoid the collisions because if that block touch the piece it lifts up the diamond needle and the machine goes out of range making the measure result in an error. The most controversial zone have been the whole 80mm radius.

To make the most precise measure (maximum length) and avoid contact (minimum length) there has to be an equilibrium between them. The measuring length can be changed, and the pivot moves more or less in consequence of the parameters selected. It can be chosen the Cut-off length and the number of cut-offs.

The cut-off length or sampling length is the distance required to make a measure, is the window size used to filter the measured profile, commonly referred to as l_c or λ_c. With every cut-off it calculates the rugosity and at the end of all the evaluation length the machine calculates the average value, the more number of sampling lengths the more accurate the result will be.

The parameters selected in this experiment have been tones that appear on **Image 34**.

Image 34. Example of a profile recorded and parameters used.

This parameters have been used in the totality of the experiments for simplicity and to safe time. λ_c is the cut-off length in mm (λ_c = 0.8mm in this case) and x8 is the number of cut-offs (N = 8 cut-offs) on top appears the normative applied for the measure and the pivot speed, on bottom right can e seen the whole evaluation length that is the number of cut-offs multiplied by the number of cut-offs

$$\lambda\mathrm{c}\ \ x\, N = Evaluation\ length$$ **(Eq. 3.5)**

$$0.8mm\ x\ 8 = 6.4mm$$ **(Eq. 3.6)**

This is a good evaluation length and didn't cause any problem at the time of catching data. More number of cut-offs caused troubles by going out of range due to making contact the tool with the piece and lifting the diamond needle. Fewer number of cut-offs would make the results lack of accuracy. The same happens with the cut-off length, a larger length would cause problems because of collision and a shorter length would make the results less true. The combination used is optima and useful for every measure done.

Image 35. Machine used

3.2.4.2. Optical measures

The second part of the measuring consists in an optical measure of the burnishing footprints. Apart from being more sophisticated and precise allows the possibility of making a surface measure . The machine, Stil Micromesure 2, is connected to a computer through two controllers. The computer has the necessary software to catch the data treat it and convert it into the rugosity values.

The machine disposes from a mobile bed like in a milling machine that can move the piece in the xy plane, then it has a light emitting device that can go up and down in the z-axis. This light is what catches the altitude from the piece by sending the ray and comparing it with the return, the machine does this point by point depending on the parameters selected in the program.

First of all it has to be calibrated the light, for that it needs a dark for reference, the light has to be covered and wait a few seconds until it sets the dark value. After that the light has to be in the centre of the burnishing footprint and the piece has be leveled. To level the piece it has to be looked at the altitude and intensity values. For a correct measure the altitude should be between 0 and 130µm and the intensity between 5 and 99% being the optimal around 30 and 50% but most of the times it can't be found such a good value and the majority are done with a 99% of intensity.

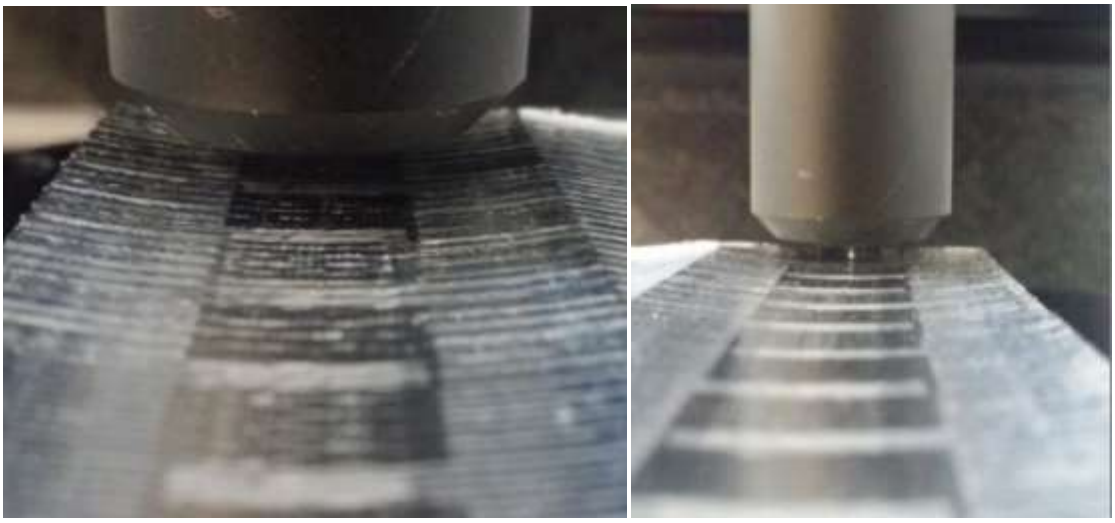


Image 36. Positioning of the light pen. On the right image can be seen the light

After reaching good levels of altitude and intensity the light should be visible on the piece(**Image 36**) and it has to proceed to click on the leveling button. It's easier if the option take measure from centre is on, this way the light will travel half distance to the left and half to the right.

The leveling option asks for a measuring distance to level the piece correctly, it has been selected 5mm instead of the 1mm default for more leveling precision. Once it starts, the lights travels in the x axis the selected distance (5mm for this specimen) and checks if the measure can be done, usually after this operation the program says that the piece must change the initial leveling, for that the bed has two screws that incline the piece, one modifying the x axis inclination and the other for the y axis. The program tells the user how much has to turn the screw. When the x axis leveling screw is turned as the program says the piece the altitude and intensity have to be adjusted again to have two good values. With this, the x axis will be leveled, after leveling in the x, the program will proceed to do the same on the y axis, first it will test the level travelling the same 5mm but this time in the y axis, it the piece needs a correction the program will tell how much has to be lifted or lowered by turning the screw in one or the other direction.

Image 37. Leveling of the bed

Image 38. The perfilometer

Once the piece is fully leveled it can be started the measuring. For measuring a profile it has to enter in the profile measuring option and select the distance to measure, the axis and the step. The measuring axis is x axis. The step is the frequency which it takes data, the more frequency is selected the more precise the result will be but it will take more time. It has been selected 10µm, that means that the data will be recorded every 10 µm. The same with the evaluation length, to more length it corresponds more precision and more time. The cut-off filter can be selected too in this program, it has been selected the same as in the contact measuring (λ_c = 0.8mm) and the number of cut-offs (5 default in the program). If there is more evaluation length than the multiple of the cut-off per the number of cut offs like in this case, that 0.8mm x 5 = 4mm < 5mm, it applies pre and post lengths, this is an extra length that is not calculated.

Now the measure would be done, next step is safe the data with a name in order to recognise it at the time of processing the data. It is important to select the mountain type of file to safe because that is what the processing program uses to get the results . For the rest of the measures it has to be repeated the process of leveling, adjusting altitude and intensity and recording the profile.

With the data saved the SPIP can use and process the information to turn it into results and graphics. The mountain file has to be selected and opened, then click on "set" and it will prepare to calculate, select the parameters to calculate and the normative then click on "calculate". When calculated it will appear a report containing all the data and can be saved into a html, also after the calculus it shows different graphics, the profile, etc.

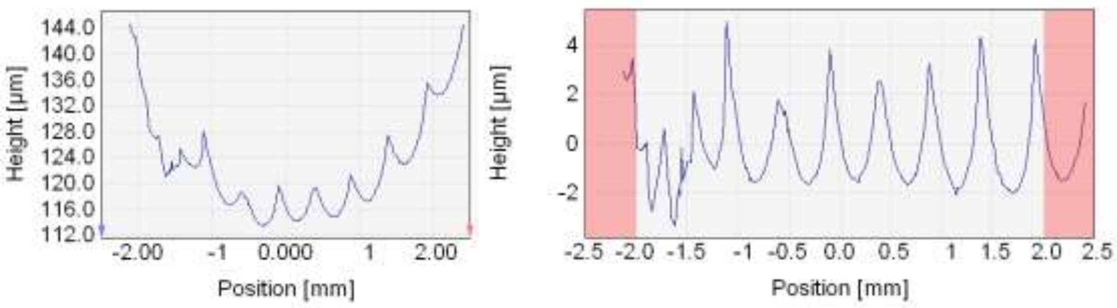


Image 39. Profiles measures. Left raw profile. Right rectified profile

For the rugosity in non flat surfaces it measures it and the transforms the profile to measure it as if it was a flat surface.

This is all for the profile measurement with the optic perfilometer but the Stil Micromesure 2 has another application, surface measurements. These are a more precise measures and give a more reliable result due to a bigger amount of data taken. Also the graphics on this type of measuring are much more visual because it can show the surface in 2D (seen in top view) and in 3D not only the profile of a line.

To perform this type of measures the piece has to be leveled, it is recommended to use the same leveling used for the profile. Measure the profile and without moving the piece or the light. then, measure the surface or vice versa, first the surface and then the profile, it doesn't affect. This will save a lot of preparation time.

When the piece is leveled it has to enter the surface mode and select the parameters. In this section there has to be selected the distance and the step in both axis, x and y. The distance selected has been 3mm in both axis making a squared measure of 3x3mm. The step has been chosen 10µm for the x axis and 50 µm for the y axis so it will catch the data every 10 µm on the x axis, jump 50 µm on the y axis and again catching data in x. The path will look like the described in

Image 40.

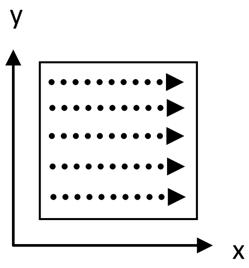


Image 40. Scheme of the data catching

The data will have to be saved again like it has been done with the profiles, and then processed with the SPIP. The procedure now is the same, open the mountain file, this time is a .sur extension, then set, calculate and save the report as a html. After calculating it appear different graphics and images as it can be the 2D surface, it's an image of the surface like a photography, taken from above, also there is an option to get a 3D view from the surface and can be rotated to see it in every direction.

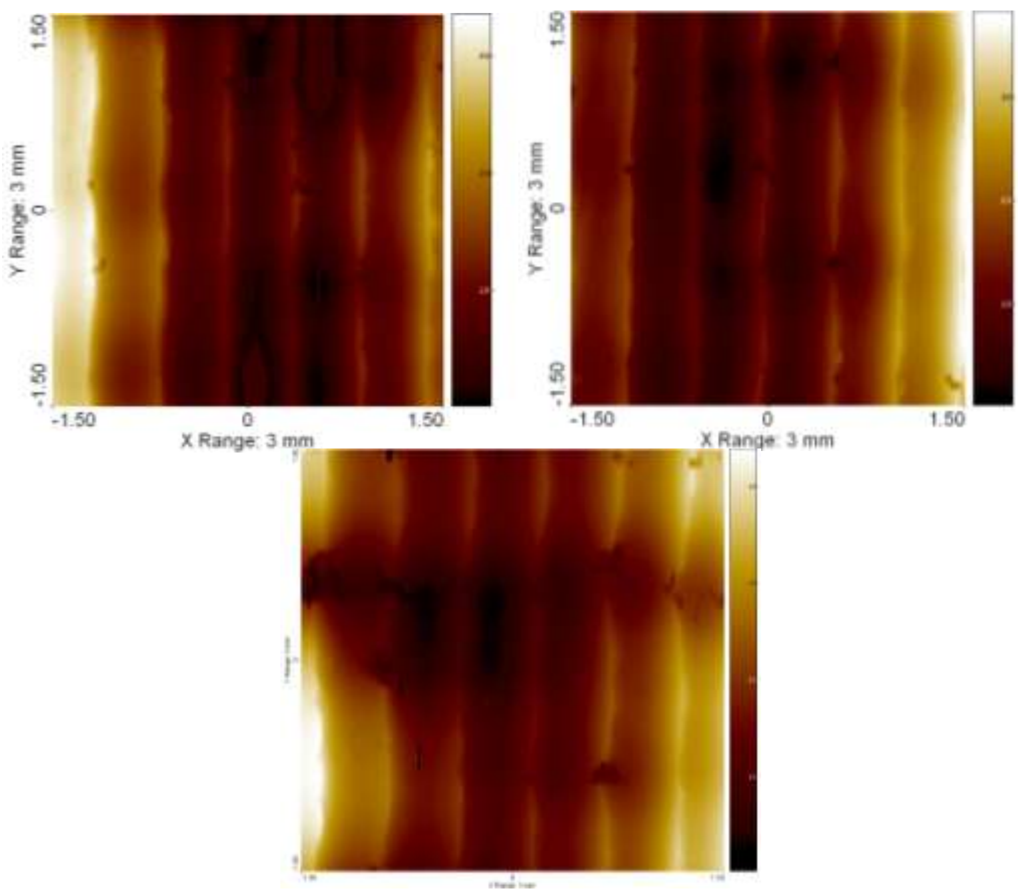


Image 41. Examples of surface images in 2D

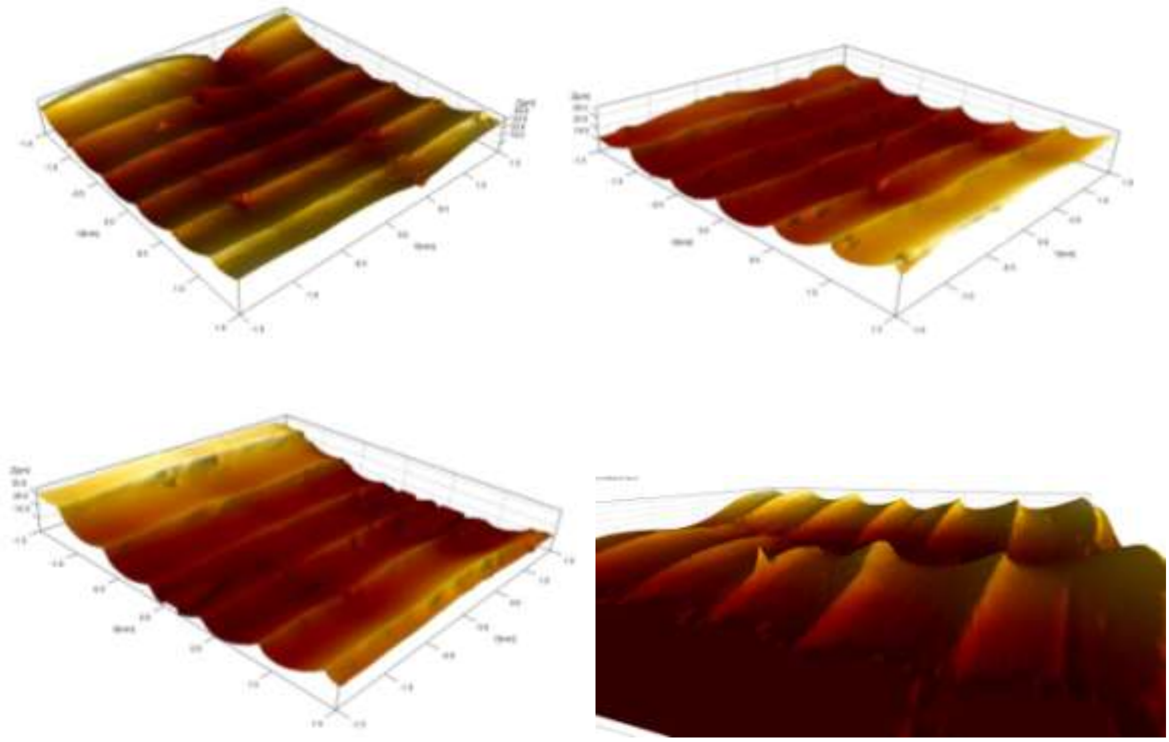


Image 42. Examples of the 3D viewing

To follow all this steps for every measure is a tedious work and takes a lot of time, the preparation consumes the biggest part of the time but the measure is slow too, for the profile only takes a few seconds but for the surface it takes around 3 minutes for each footprint making it hard to take many measures from the same footprint.

With this all the data has been taken and it's time to process it and compare the results:

4. Data treatment

All the data have been recorded. With all those variables it can be compared the performance of both measuring machines and the capability of the ball burnishing tool in concave geometries.

First the measuring methodologies will be compared

4.1. Comparing the methodologies

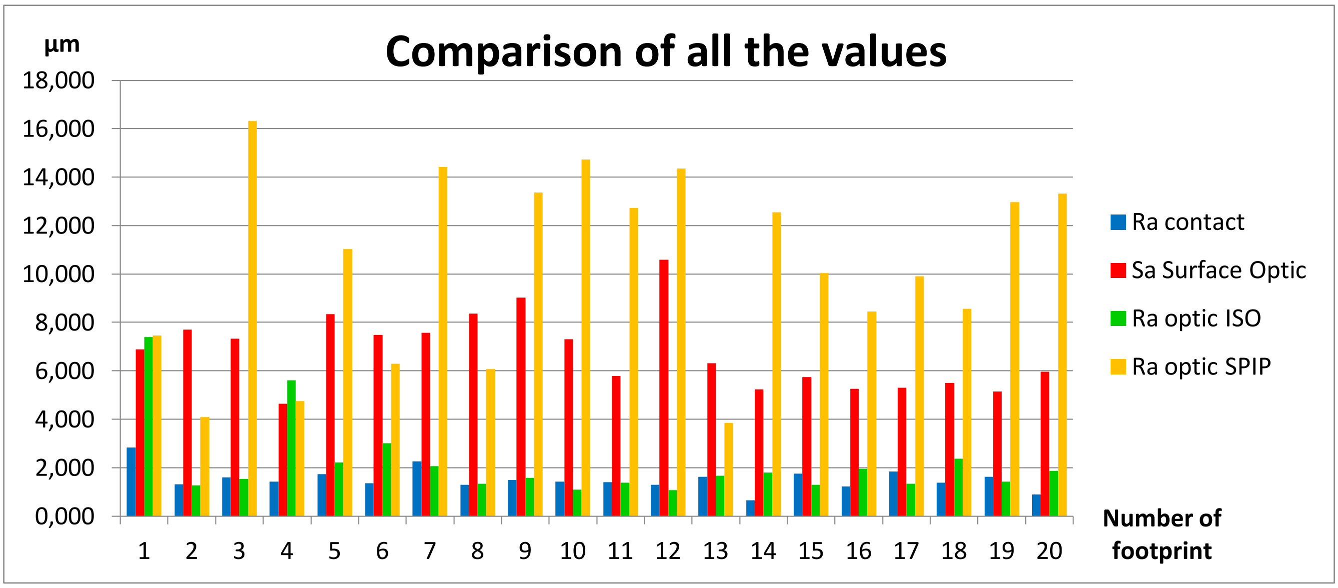
	Contact ISO 4287:1997		Optic ISO 4287:1997		Surface SPIP CLASSIC		Profile SPIP CLASSIC	
	Ra	Rq	Ra	Rq	Sa	Sq	Ra	Rq
Footprint 1	2,832	3,424	7,401	9,476	6,8973	8,812	7,4638	8,4768
Footprint 2	1,303	1,599	1,27	1,653	7,6917	9,3117	4,0806	4,9482
Footprint 3	1,593	1,924	1,531	1,836	7,3234	9,0221	16,313	18,645
Footprint 4	1,423	1,792	5,613	8,753	4,629	5,701	4,7605	5,9672
Footprint 5	1,726	2,038	2,219	2,667	8,3319	10,534	11,038	13,283
Footprint 6	1,365	1,69	3,002	5,932	7,4924	9,3481	6,2975	7,4111
Footprint 7	2,25	2,836	2,064	2,854	7,5758	9,0742	14,42	16,132
Footprint 8	1,282	1,541	1,329	1,609	8,3629	10,458	6,0787	7,6165
Footprint 9	1,488	1,876	1,576	1,888	9,0185	10,82	13,37	15,716
Footprint 10	1,426	1,788	1,093	1,402	7,3008	8,8051	14,72	16,654
Footprint 11	1,403	1,789	1,381	1,665	5,7938	7,1475	12,734	15,002
Footprint 12	1,294	1,608	1,078	1,439	10,595	12,604	14,349	16,592
Footprint 13	1,629	1,966	1,662	2,684	6,3195	9,5059	3,8468	4,9051
Footprint 14	0,652	1,327	1,802	2,141	5,2443	6,6237	12,554	14,285
Footprint 15	1,748	2,143	1,281	1,587	5,7409	7,1564	10,046	11,902
Footprint 16	1,225	1,483	1,957	2,505	5,2546	6,9955	8,4588	9,9961
Footprint 17	1,853	2,315	1,334	1,579	5,2926	6,2389	9,9092	11,653
Footprint 18	1,389	1,661	2,36	3,804	5,4882	6,4262	8,568	9,8569
Footprint 19	1,621	1,968	1,42	1,82	5,1389	6,2446	12,972	14,958
Footprint 20	0,898	1,33	1,875	2,234	5,9603	7,1751	13,317	15,208

Table 11. Comparison among all the values of Ra and Rq variables for both systems, SPIP Classic and ISO 4287:1997

Having all the results it can be reasoned the best conditions to be applied, for that it will only be taken into account the measures taken by the normative ISO 4287:1997 because it's the international official standard, but first it will be analyzed the behaviour of the machine for the SPIP CLASSIC.

For the profile the Ra results vary from around 4µm to around 16µm, for the surface the values of Sa are less disperse, oscillating between 4.6µm and 10.5µm. In comparison with the ISO 4287:1997 the values are much more high, in the ISO the values range goes from around 1 to around 3µm (7 µm from footprint 1 on the optic measure has an error). Although the measures are not as reliable as they should be the surface measuring has a very good plus point which is the visualization system that lets see the surface augmented and it's a very visual way to see the rugosity of the piece.

All the data is compared below:

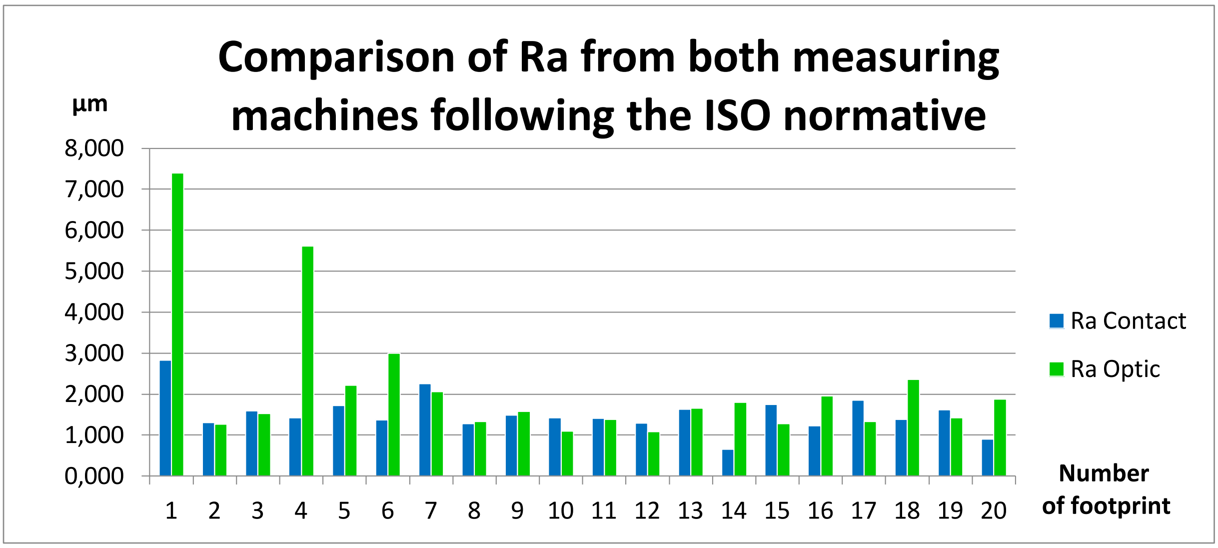


Graphic 1. Comparison of the roughness

In every measure the Sa (red) and Ra optic by SPIP Classic (yellow) give a much higher value of rugosity except for those optic measures with an error (1 and 4) that the furthest value is the Ra by contact, with that there is bad reliability of the results for the surface and Ra optic SPIP measures, mostly because of the different normative that governs it. The ISO measures show a more comparable results in all the footprints.

The non ISO measures although are not reliable values re higher when the surface is rougher and lower when the surface is smoother, it's like these measures have been taken in a different scale so if the numerical value is not important and there is interest in the comparison among surfaces the SPIP Classic is not a wrong way to measure although it is more recommended to use the ISO normative.

The ISO measures will be isolated for a better visualization:

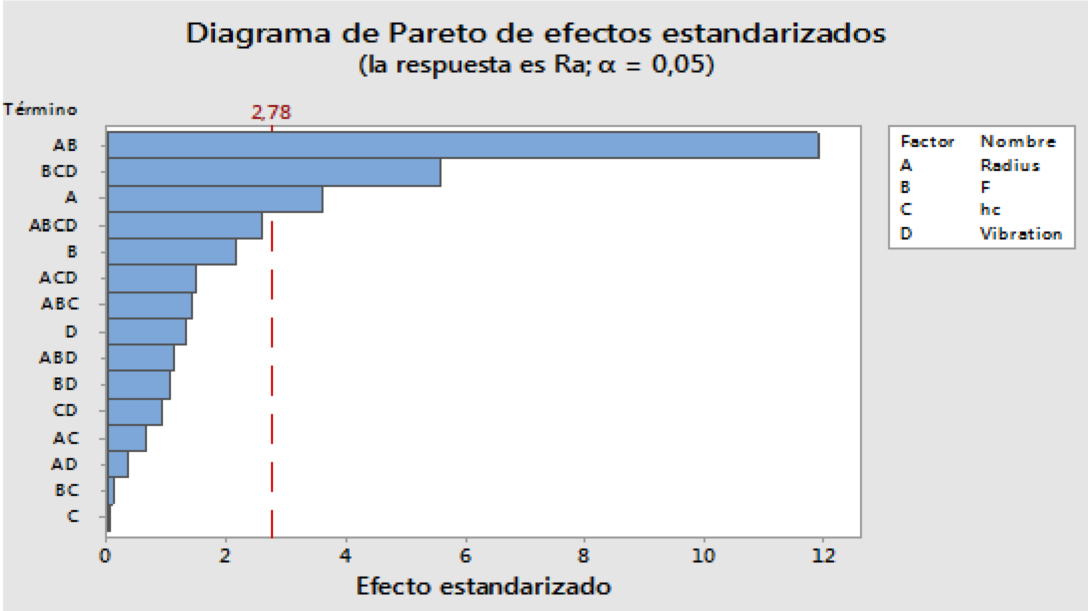


Graphic 2. Comparison of Ra from both measuring machines by the ISO 4287:1997.

Footprints 1, 4 and 14 too, show a significant dispersion, which can be due to a measuring error. It makes sense that the error appeared in the optical perfilometer because the contact rugosimeter has a more stable behaviour and also has had more measures from the same footprint and has more statistical reliability. Not the footprint 14, this has an error on the contact measures because the behaviour of all other measures is similar in **Graphic 1**, that is why the other measures are usefull too, to detect possible errors. Apart from those measures the rest of the graphic shows a much more matched distribution.

4.2. Comparison the parameters

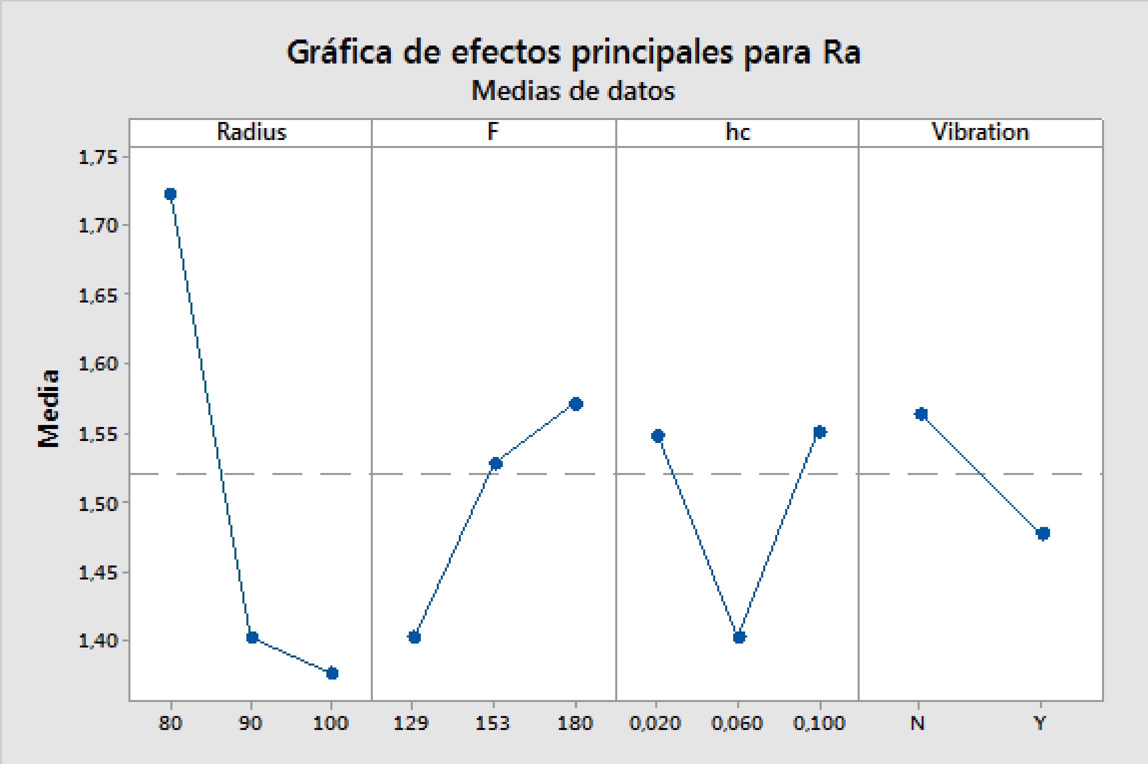
Once compared the measuring machines it's time to compare the parameter combination and the most influence parameter. For that a statistical study is done. Below it is shown the combination of parameters that influence the most



Graphic 3. Pareto's diagram of standardized effects for Ra

Pareto's diagram classifies the issues from the most influential to least. The legend at right assigns a letter to every variable and in the ordinates axis every combination of parameters. The most influential combination is the radius and the force and is a lot more than the second. The most influential parameter without combination is the curvature radius. The least influential, unlike it was thought, is the previous surface quality.

With that it is known the most and least influential parameter but not how influences, for that the principal effect graphic shows the best value for every variable:

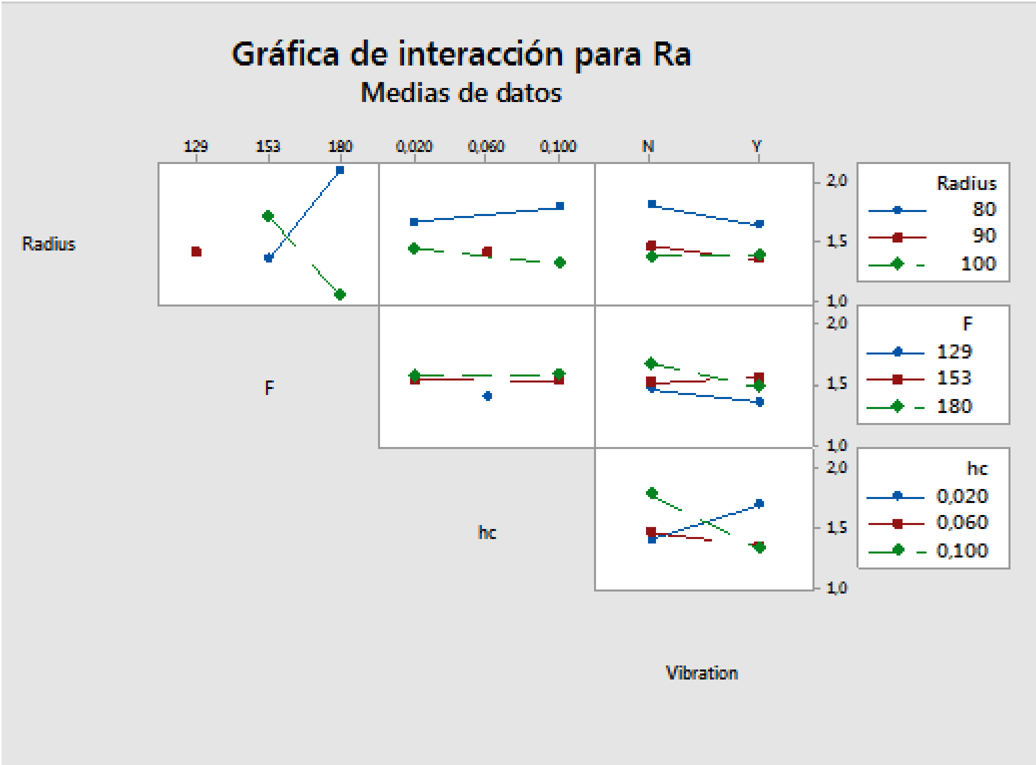


Graphic 4. Principal effect graphic for Ra

The **Graphic 4** separates every variable. In the ordinate axis there is the rugosity and in the abscises axis the values for every variable, if the point is the lower for a variable means that it's the best value for it because leads to the smallest roughness.

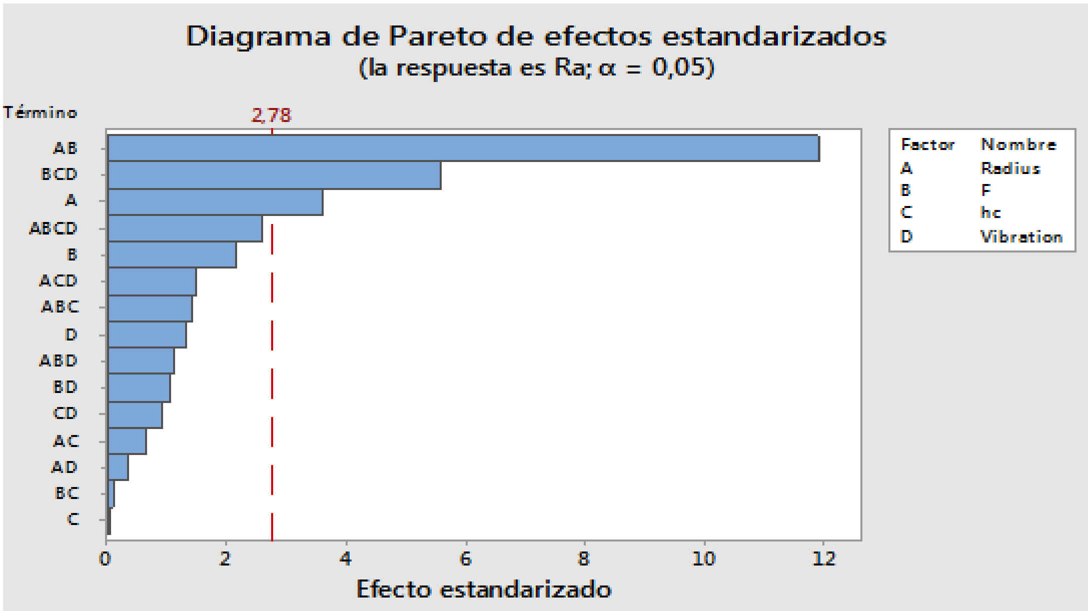
Seeing the **Graphic 4** the best parameters are 100mm radius, 129N, hc=0.06mm and vibration ON. Unfortunately this footprint doesn't exist because 129N and hc=0.06 only belong to the central zone that has a 90mm radius, but this radius is very close to the 100mm radius in the graphic so if changing the 100mm to a 90mm radius the footprint is number 11 and 12 (both are exactly the same) and effectively footprint 12 is one of the best surfaces

Finally a graphic of the parameter interaction is shown:.



Graphic 5. Interaction graphic for Ra

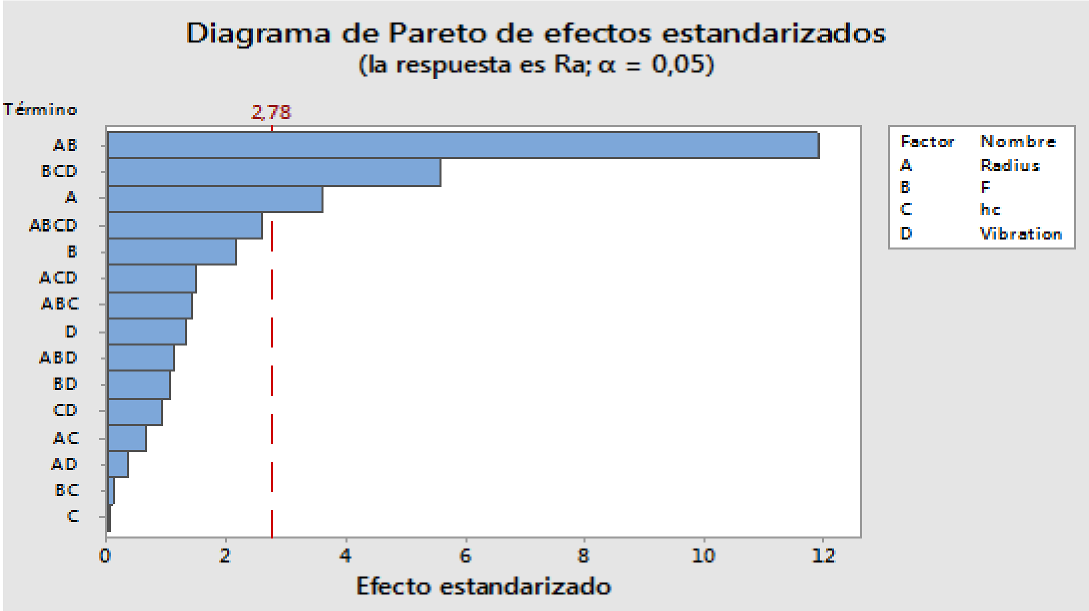
In **Graphic 5** appears the combination of parameters in pairs and its influence in the roughness. If the lines have a little slope and are almost horizontal that means that the parameters are not very influent, as happens with hc and F , F and vibration or hc and Radius. As it appeared on the



Graphic 3, hc is the less influent. Opposite if the lines are very inclined like in Radius and F the

parameters are the most influent, as happened on Pareto's diagram, being F=180N and radius=100mm the combination that gives the least roughness.

This graphic is a corroboration of Pareto's diagram showing the best values for the variables, it's like a combination of

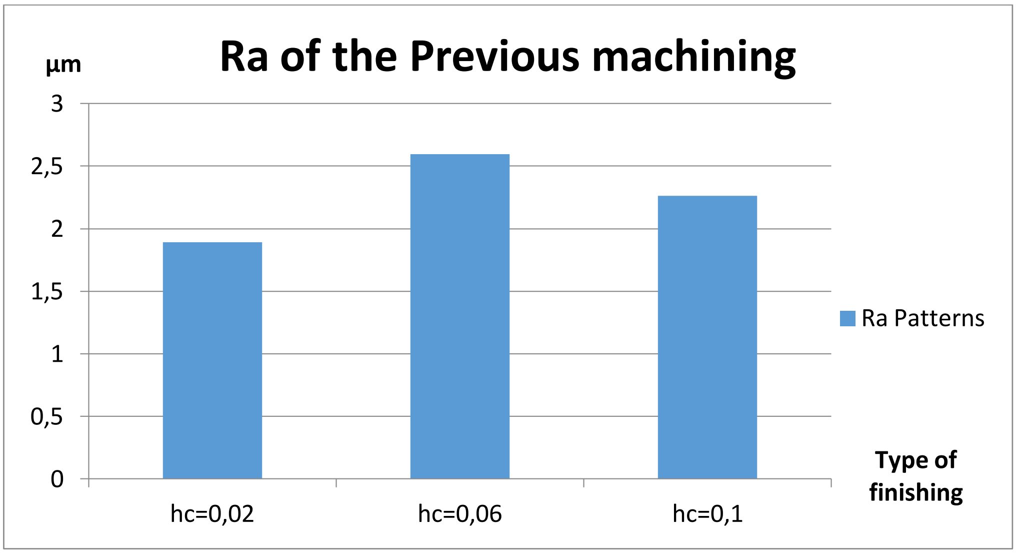


Graphic 3 and **Graphic 4** but less clear because it's all mixed.

4.3. Improvement from the previous machining

The burnishing is a quality surface improving process and in this section it is going to be evaluated the improvement of the surface, for that it is going to be presented the previous surface quality and then the range of upgrade depending if it is the best or the worst burnished surface.

The previous machining has three different finishes, the hc=0.02, hc=0.06 and hc=0.1 to every finish it correspond one Ra:



Graphic 6. Ra for every previous machining

For hc=0.06 µm correspond the highest Ra, it was thought that the highest Ra would correspond to the hc=0.1 µm, the reason of this may be that to make a higher crest the tool needs a bigger depth and as it is a spherical mill it separates more the two crests making the distance peak-valley bigger but the separation between crests bigger too, and for the average roughness its better.

The comparison with the posterior surface will be separated by the type of finishing.

hc=0.02µm:

It has a Ra=1.89 µm and the burnishes go from 1.85 µm of the worst (footprint 17)t to 0.89 µm of the best (footprint 20). Footprints 1 is not taken into account because it gets the surface worse, so for hc=0.02 µm the improvement is **between a 2% and a 53%.**

hc=0.06µm:

It is exclusive from the central area and has a Ra=2.59 µm, the burnishes in that area are between 1.48 µm (footprint 9) and 1.29 µm (footprint 12). The improvement is around a **42.8% and a 50%**

hc=0.1 µm:

The Ra on this zone is 2.26 µm and the burnishings vary between 2.2 µm from worst (footprint 7) and 1.22 µm (footprint 16). The 0.6 µm form footprint 14 are not taken into account. The surface is improved between a **2.6% and a 46%**.

What is important to see is that all the burnishings improve the surface, some of them considerably.

5. Environmental impact analysis

The manufacturing of the piece starts from a raw block of aluminium. Achieving the required geometry is done trough a mill, that is, a material removing method. This removed material is dispended in chip. The machine is closed so the chip that tries to get out hits the doors and falls to the bottom of the machine.

After the process this chip is collected and deposited in its container, in the workshop there are three different containers for scrap metal, one for aluminium, one for steel and the other for titanium because these three are the materials commonly used. In this case the chip goes to the aluminium container, once the container is full it is treated as usual scrap.

If a machining error appears as it has happened it can be machined again on the same raw material, the machine only has to be prepared again but there is no necessity of a new block.

The cutting fluid is kept in a 70l deposit in the bottom of the machine and feeds the system. When the fluid starts to circulate it is shouted to the tool and the piece to refrigerate and lubricate it. The cutting fluid leaks to the bottom of the machine and enters the deposit again through a filter so the chip does not mixes the cutting fluid.

Because of the low use of the machine the fluid doesn't degrade so much and the substitution can be done twice a year. In the industry the substitution of the cutting fluid because of the loss of properties it's done every 3 months or less if the machine uses it very frequently. The substitution consists on emptying the deposit into a container and an external company hired to treat waste comes to collect it for its correct recycling.

The cutting fluid is mostly water, it contains around a 4% of oil for lubrication also it contains other additives to avoid corrosion and rusting the pieces, tools and mechanisms. The recycling consists on separating the water and treating the oil and other substances following the current normative.

Besides the chip and the cutting fluid this project has no more impact on the environment because the burnishing is a clean procedure that works in cold and without chip removal and the measure leaves no residue. The only effect on the environment is the electric power needed to use the machines, both the CNC milling machine and the rugosimeters. The measuring doesn't need so much power but the machining centre has a higher demand, ideally it all should be powered by clean and renewable energy but unfortunately this is not the case.

Conclusions

One of the objectives of this project is to compare the two measuring machines, differences, pros and cons. It has been seen in Graphic 1 that the behaviour is similar in all the measures but the numerical value only is similar if the measure follows the ISO 4287:1997 normative. Contact rugosimeter is way faster to use and with that allows the possibility of more measures, more measures mean more reliability in the results. Although the surface measuring allows a 3D view very useful.

Another objective is to prove the tool, for that different parameters have been changed. The final results haven't been as expected. It was expected that the best parameters would be the high force, good previous surface quality, high curvature radius and vibration on but the results haven't been those. The most influential parameter is the radius, that is a logical result but the previous surface quality appears to be the least influential and it has been thought to be one of the most.

This discordances between the expected and the results may be due the changes from test 1 to test 2. The augmented surface is a good thing for sure but the reduction of the force applied is not the best solution, it was a decision made for fear to the tool getting stuck and to ensure the gliding of the ball. Also most of the surfaces present imperfections, like valleys without burnish, specially on the central zone, this is because of the light forces applied and may be the cause of the unexpected results. This will be discussed in the improvement proposal section.

The project is an experimental project and is attached to errors, it's not considered something fatal to find some problems and it's important and very positive to know how to fix them and keep going on as quickly as possible to not lose time.

Another conclusion of the project, more secondary, is that it has been seen that this procedure is much faster than the machining, it takes an 80% less time. It is an automatable operation that doesn't require personal working apart from setting the machine and that translates into a money saving that is what the industry searches.

Improvement proposal

As the project didn't end as good as expected in this section there are compiled the possible improvements for a better results.

For the burnishing the first thing to avoid it collision so the cap of the ball burnishing tool could be thinner and it would leave more space for the burnishing and let do bigger burnishing surfaces.

For the measures a similar thing happens, as seen in **Image 33**. Detail of the measure on front view.**Image 33**, the frontal block makes contact with the piece and lifts up the diamond needle making the measure go out of range. If that block would be smaller it wouldn't hit the piece until a few millimetres later enlarging the measuring length and with it the precision.

For the optical perfilometer one thing that could be changed is the leveling bed, that is adjusted by two screws with low precision and are quite hard to turn. Also the inclination is not very high and has a limitation in strange geometries needing a lift putting another object under the piece to incline it even more.

Image 43. Extra inclination with a pen

Finally the best improvement should be the increment of the forces returning to the original configuration. The central zone with the smaller force appeared to have a very light burnishing, the burnished zones have a good surface quality but some of the valleys of the previous machining are left without burnish, in the other two forces all the surface have been burnished but still there are some points that don't shine like the rest of the surface. A heavier force would correct this. Having an homogeneous completely burnished surface would end in a more expected results. Also making more different tests on the central zone would be interesting to have more data.

Budged

The project has to be evaluated economically, to do this the items are going to be described and at the end a table will show the compilation of everything.

4.4. Chapter 1. Technical office

The technical office work is the job done by the engineer, calculating, researching, reasoning the results, etc. The work has been done by a training engineer and it's price is around 6 and 10€ per hour.

4.5. Chapter 2. Laboratory work

In this chapter it is compiled the manual work and the operator's price, instead of a qualified operator the same training engineer does the handwork for the same price. The price from the machines and its use comes in another chapters.

4.6. Chapter 3. Material

The material chapter contains the price for the material used, the machines, the tools and the specimen to perform the experiments on.

4.7. Chapter 4. Energetic cost

Here goes the cost from the electric bills for the machine-tools used, the measure devices have been despised because the power consume doesn't affect much in the global budged.

4.8. Chapter 5. Various

In all the budget there has to be taken into account the possible extra costs, that could be caused by accidents, extra work, new material because of a planning error. This cost is represented as an extra percent of the total, for this project with low incident level a 10% of the total has been selected for the possible various extra costs.

A table shows all the costs by chapter:

Chapter 1	**Technical Office**				
	Name	Description	hours	Price(€)/hour	Total (€)
	Office work	Research of information, study, calculus, etc.	230	10	2300
Chapter 2	**Laboratory work**				
	Name	Description	Units	Price/Unit	Total (€)
	Machining	Machining work done by an intern	3	10	30
	Burnishing	Burnishing work done by an intern	0,5	10	5
	Measuring	Measuring done an intern	26	10	260
Chapter 3	**Material**				
	Name	Description	Units	Price(€)/Unit	Total (€)
	Raw material	Block of aluminium A2017 100x80x16mm	1	50	50
	CNC LAGUN MC	CNC milling machine	1	20000	20000
	Spheric mill 8mm	Spheric mill 8mm diameter 2 cutting edges	1	35	35
	Ball burnishing tool	Ball burnishing tool aided by ultrasounds	1	2500	2500
	Mitutoyo Surftest SJ-210	Contact rugosimeter	1	2215	2215
	SPIP Micromesure 2	Optical Perfilometer with its controllers	1	9000	9000
	Computer	PC to control the perfilometer and process the data	1	350	350
	Ceus Textil	Wave generator	1	90	90
Chapter 4	**Energetic cost**				
	Name	Description	Units(kW)	Price(€)/hour	Total (€)
	Machining	Power of 40kW during 3 hours	120	0,12	14,4
	Burnishing	Power of 40kW during 0,5 hours	20	0,12	2,4
Chapter 5	**Various**				
	Name	Description	Units(kW)	Price(€)/Unit	Total (€)
	Other	Variable costs for unexpected expenses	1	10% from total	3685,18
Chapter 6	**Total**				
					40536,98

Table 12. Budged summary.

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TREBALL FI DE GRAU

Grau en Enginyeria Mecànica

STUDY OF SUPERFICIAL TEXTURES ON CONCAVE PIECES OF ALUMINIUM A2017

Annexes

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Director: Daniel Romanillos Delgado
Convocatòria: Juny 2018

Annex I Normative

Normative used for the measuring process:

ISO 4287:1997 Geometrical Product Specifications (GPS) — Surface texture: Profile method — Terms, definitions and surface texture parameters

Normative used for the machining process:

ISO 16090-1:2017 Machine tools safety — Machining centres, Milling machines, Transfer machines

Normative used for the bibliography:

UNE-ISO 690:2013 Information and documentation. Guidelines for bibliographic references and citations to information resources

Annex II Material Properties

-2017 A- (ALUMINIO – COBRE)

COMPOSICIÓN QUÍMICA

%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Otros elementos	Al
Mínimo	0,20		3,50	0,40	0,40				Zr+Ti Total	
Máximo	0,80	0,70	4,50	1,00	1,00	0,10	0,25		0,25 0,15	El resto

PROPIEDADES MECÁNICAS TÍPICAS (a temperatura ambiente de 20ºC)

		Características a la tracción					Dureza	
Estado	Espesor mm	Carga de rotura Rm, N/mm2	Límite elástico Rp 0,2, N/mm²	Alargamiento A 5,65%	Límite a la fatiga N/mm²	Resistencia a la cizalladura T N/mm²	Brinell (HB)	Vickers
0	0,35 < e < 12	180	70	20	180	125	45	
T4	0,35 < e < 12	425	275	15	260	275	105	
T4/T451	6 < e < 12	390	265	13	260	275	105	
T451	6 < e < 40	385	245	12	260	275	105	

PROPIEDADES FÍSICAS TÍPICAS (a temperatura ambiente de 20ºC)

Módulo elástico N/mm²	Peso específico g/cm³	Intervalo de fusión ºC	Coeficiente de dilatación lineal 1/10⁻⁶ K	Conductividad térmica W/m K	Resistividad eléctrica a 20ºC - µΩ cm	Conductividad electrica % IACS	Potencial de disolución V
72,500	2,79	510-645	22,9	135	0-34	T4-34	-0,69
					T4-5,0		

APTITUDES TECNOLÓGICAS

SOLDADURA:
- A la llama
- Al arco bajo gas argón
- Por resistencia eléctrica
- Braseado

MECANIZACIÓN: Estado:T4
- Fracmentación de la viruta
- Brillo de superficie

COMPORTAMIENTO NATURAL:
- En ambiente rural
- En ambiente industrial
- En ambiente marino
- En agua de mar

RECUBRIMIENTO:
- Lacado
- Galvanizado
- Niquel químico

ANODIZADO:
- De protección
- Decorativo
- Anodizado duro

Muy buena.
Buena.
Regular.
Mala,evitar.

RADIOS DE PLEGADO

Estado	0,4<e<0,8 mm.	0,8<e<1,6 mm	1,6<e<3,2 mm.	3,2<e<4,8 mm.	4,8<e<6 mm.	6<e<10 mm.	10<e<12 mm.
0	0	0	0,75	1	1,5	2,5	4
T4	2,5	3	4	5	5	6	-

Multiplicar el coeficiente por el espesor (e) de la chapa

-2017 A- (ALUMINIO - COBRE)

CARACTERÍSTICAS MECÁNICAS DE LA ALEACIÓN A DIFERENTES TEMPERATURAS

Estado	-195ºC			-80ºC			-30ºC			+25ºC			+100ºC		
	Rm	Rp 0,2	A 5,65	Rm	Rp 0,2	A 5,65	Rm	Rp 0,2	A 5,65	Rm	Rp 0,2	A 5,65	Rm	Rp 0,2	A 5,65
T4	550	365	28	450	290	24	440	285	23	425	275	22	395	270	18

Estado	+150ºC			+205ºC			+260ºC			+315ºC			+370ºC		
	Rm	Rp 0,2	A 5,65	Rm	Rp 0,2	A 5,65	Rm	Rp 0,2	A 5,65	Rm	Rp 0,2	A 5,65	Rm	Rp 0,2	A 5,65
T4	275	205	15	110	90	35	60	50	45	41	34	65	30	24	70

Rm N/mm^2 ; Rp N/mm^2 ; A 5,65 %

Según normas A.A.

TRATAMIENTOS DEL ALUMINIO

Estado	Tratamiento de puesta en solución TºC	Medio de temple	Tratamientos de maduración artificial. Mantenimiento a Tª en horas	Maduración natural.
T4	505ºC± 5 ºC	Agua fría máx. a 40ºC		4 días mínimo

Intervalo de temperatura de forja: 380º – 460ºC

Recocido total: 420ºC, con enfriamiento lento hasta 250ºC

Recocido contra acritud: 340ºC

APLICACIONES

Elementos estructurales que requieren elevadas características mecánicas, aviación, construcción en general, herrajes, tornillos, pernos, remaches para ser aplicados en estado de temple antes de la maduración, troqueles, moldes, maquinaria, herramientas, etc.

OBSERVACIONES

Esta aleación no está recomendada para el anodizado pues queda de un color marrón claro. El estado T451 se utiliza normalmente a partir de 8mm y consiste en una tracción controlada después del tratamiento para eliminar tensiones.

Annex III Results tables

	Ra	Rq	Rz	Rt
Footprint 1	2,832	3,424	13,954	19,966
Footprint 2	1,303	1,599	7,252	10,216
Footprint 3	1,593	1,924	8,209	10,925
Footprint 4	1,423	1,792	8,327	13,637
Footprint 5	1,726	2,038	9,165	11,783
Footprint 6	1,365	1,690	7,760	11,884
Footprint 7	2,250	2,836	12,830	24,814
Footprint 8	1,282	1,541	6,969	9,131
Footprint 9	1,488	1,876	9,044	18,604
Footprint 10	1,426	1,788	8,397	12,255
Footprint 11	1,403	1,789	8,386	12,777
Footprint 12	1,294	1,608	7,350	10,321
Footprint 13	1,629	1,966	8,303	10,928
Footprint 14	0,652	1,327	5,809	8,181
Footprint 15	1,748	2,143	9,129	11,951
Footprint 16	1,225	1,483	6,537	8,618
Footprint 17	1,853	2,315	9,666	12,842
Footprint 18	1,389	1,661	7,509	11,746
Footprint 19	1,621	1,968	8,300	11,127
Footprint 20	0,898	1,330	5,737	8,404

Table 13. Profile by contact measures following the ISO 4287:1997

To order the footprints from best quality to worst it's done by the Ra which is the most general variable and all other variables will be ordered approximately from best to worst. When showing the ordination it also will be shown the parameters associated. The table looks like this:

	Ra	Rq	Rz	Rt	Radius	F	hc	Vibration
Footprint 14	0,652	1,327	5,809	8,181	100	180	0,100	Y
Footprint 20	0,898	1,330	5,737	8,404	100	180	0,020	N
Footprint 16	1,225	1,483	6,537	8,618	100	180	0,100	N
Footprint 8	1,282	1,541	6,969	9,131	80	153	0,020	Y
Footprint 12	1,294	1,608	7,350	10,321	90	129	0,060	Y
Footprint 2	1,303	1,599	7,252	10,216	80	153	0,100	N
Footprint 6	1,365	1,690	7,760	11,884	80	153	0,020	N
Footprint 18	1,389	1,661	7,509	11,746	100	180	0,020	Y
Footprint 11	1,403	1,789	8,386	12,777	90	129	0,060	Y
Footprint 4	1,423	1,792	8,327	13,637	80	153	0,100	Y
Footprint 10	1,426	1,788	8,397	12,255	90	129	0,060	N
Footprint 9	1,488	1,876	9,044	18,604	90	129	0,060	N
Footprint 3	1,593	1,924	8,209	10,925	80	180	0,100	Y
Footprint 19	1,621	1,968	8,300	11,127	100	153	0,020	N
Footprint 13	1,629	1,966	8,303	10,928	100	153	0,100	Y
Footprint 5	1,726	2,038	9,165	11,783	80	180	0,020	N
Footprint 15	1,748	2,143	9,129	11,951	100	153	0,100	N
Footprint 17	1,853	2,315	9,666	12,842	100	153	0,020	Y
Footprint 7	2,250	2,836	12,830	24,814	80	180	0,020	Y
Footprint 1	2,832	3,424	13,954	19,966	80	180	0,100	N

Table 14. Profile results by contact rugosimeter in order from best Ra to worst with its parameters associated

For the optic measure of the profile:

	Ra	Rq	Rz	Rt
Footprint 1	7,401	9,476	19,627	24,323
Footprint 2	1,27	1,653	6,947	9,503
Footprint 3	1,531	1,836	6,217	8,399
Footprint 4	5,613	8,753	21,843	27,342
Footprint 5	2,219	2,667	9,505	10,846
Footprint 6	3,002	5,932	4,559	19,361
Footprint 7	2,064	2,854	11,964	21,568
Footprint 8	1,329	1,609	5,827	8,275
Footprint 9	1,576	1,888	7,193	10,45
Footprint 10	1,093	1,402	5,952	8,244
Footprint 11	1,381	1,665	6,034	7,722
Footprint 12	1,078	1,439	5,954	8,528
Footprint 13	1,662	2,684	6,371	18,388
Footprint 14	1,802	2,141	7,569	10,276
Footprint 15	1,281	1,587	6,208	8,097
Footprint 16	1,957	2,505	8,266	21,588
Footprint 17	1,334	1,579	6,191	9,398
Footprint 18	2,36	3,804	8,192	19,154
Footprint 19	1,42	1,82	7,099	10,275
Footprint 20	1,875	2,234	8,134	9,737

Table 15. Profile by optical measures following the ISO 4287:1997

In order:

	Ra	Rq	Rz	Rt	Radius	F	hc	Vibration
Footprint 12	1,078	1,439	5,954	8,528	90	129	0,06	Y
Footprint 10	1,093	1,402	5,952	8,244	90	129	0,06	N
Footprint 2	1,27	1,653	6,947	9,503	80	153	0,1	N
Footprint 15	1,281	1,587	6,208	8,097	100	153	0,1	N
Footprint 8	1,329	1,609	5,827	8,275	80	153	0,02	Y
Footprint 17	1,334	1,579	6,191	9,398	100	153	0,02	Y
Footprint 11	1,381	1,665	6,034	7,722	90	129	0,06	Y
Footprint 19	1,42	1,82	7,099	10,275	100	153	0,02	N
Footprint 3	1,531	1,836	6,217	8,399	80	180	0,1	Y
Footprint 9	1,576	1,888	7,193	10,45	90	129	0,06	N
Footprint 13	1,662	2,684	6,371	18,388	100	153	0,1	Y
Footprint 14	1,802	2,141	7,569	10,276	100	180	0,1	Y
Footprint 20	1,875	2,234	8,134	9,737	100	180	0,02	N
Footprint 16	1,957	2,505	8,266	21,588	100	180	0,1	N
Footprint 7	2,064	2,854	11,964	21,568	80	180	0,02	Y
Footprint 5	2,219	2,667	9,505	10,846	80	180	0,02	N
Footprint 18	2,36	3,804	8,192	19,154	100	180	0,02	Y
Footprint 6	3,002	5,932	4,559	19,361	80	153	0,02	N
Footprint 4	5,613	8,753	21,843	27,342	80	153	0,1	Y
Footprint 1	7,401	9,476	19,627	24,323	80	180	0,1	N

Table 16. Profile results by optical rugosimeter in order from best Ra to worst with its parameters associated

For the surface measuring:

	Sa	Sq
Footprint 1	6,8973	8,812
Footprint 2	7,6917	9,3117
Footprint 3	7,3234	9,0221
Footprint 4	4,629	5,701
Footprint 5	8,3319	10,534
Footprint 6	7,4924	9,3481
Footprint 7	7,5758	9,0742
Footprint 8	8,3629	10,458
Footprint 9	9,0185	10,82
Footprint 10	7,3008	8,8051
Footprint 11	5,7938	7,1475
Footprint 12	10,595	12,604
Footprint 13	6,3195	9,5059
Footprint 14	5,2443	6,6237
Footprint 15	5,7409	7,1564
Footprint 16	5,2546	6,9955
Footprint 17	5,2926	6,2389
Footprint 18	5,4882	6,4262
Footprint 19	5,1389	6,2446
Footprint 20	5,9603	7,1751

Table 17. Surface rugosity by optical measures following the SPIP CLASSIC

	Sa	Sq	Radius	F	hc	Vibration
Footprint 4	4,629	5,701	80	153	0,1	Y
Footprint 19	5,1389	6,2446	100	153	0,02	N
Footprint 14	5,2443	6,6237	100	180	0,1	Y
Footprint 16	5,2546	6,9955	100	180	0,1	N
Footprint 17	5,2926	6,2389	100	153	0,02	Y
Footprint 18	5,4882	6,4262	100	180	0,02	Y
Footprint 15	5,7409	7,1564	100	153	0,100	N
Footprint 11	5,7938	7,1475	90	129	0,060	Y
Footprint 20	5,9603	7,1751	100	180	0,02	N
Footprint 13	6,3195	9,5059	100	153	0,100	Y
Footprint 1	6,8973	8,812	80	180	0,100	N
Footprint 10	7,3008	8,8051	90	129	0,06	N
Footprint 3	7,3234	9,0221	80	180	0,100	Y
Footprint 6	7,4924	9,3481	80	153	0,02	N
Footprint 7	7,5758	9,0742	80	180	0,020	Y
Footprint 2	7,6917	9,3117	80	153	0,1	N
Footprint 5	8,3319	10,534	80	180	0,020	N
Footprint 8	8,3629	10,458	80	153	0,02	Y
Footprint 9	9,0185	10,82	90	129	0,060	N
Footprint 12	10,595	12,604	90	129	0,06	Y

Table 18. Surface results by optical rugosimeter in order from best Sa to worst with its parameters associated

Sa and Sq are the equivalent to Ra and Rq respectively, it can be seen that there is a significant difference between the values, this is because the normative applied for the measuring. The contact rugosimeter uses the ISO 4287:1997. The optical perfilometer has the option to use this normative only for the profile measuring, not for the surface measuring, this last one is measured by the SPIP Classic, which is the program's own measuring methodology, this can be used for the profile measuring, the results are shown below:

	Ra	Rq
Footprint 1	7,4638	8,4768
Footprint 2	4,0806	4,9482
Footprint 3	16,313	18,645
Footprint 4	4,7605	5,9672
Footprint 5	11,038	13,283
Footprint 6	6,2975	7,4111
Footprint 7	14,42	16,132
Footprint 8	6,0787	7,6165
Footprint 9	13,37	15,716
Footprint 10	14,72	16,654
Footprint 11	12,734	15,002
Footprint 12	14,349	16,592
Footprint 13	3,8468	4,9051
Footprint 14	12,554	14,285
Footprint 15	10,046	11,902
Footprint 16	8,4588	9,9961
Footprint 17	9,9092	11,653
Footprint 18	8,568	9,8569
Footprint 19	12,972	14,958
Footprint 20	13,317	15,208

Table 19. Profile by optical measures following the SPIP CLASSIC

It only appears the Ra and Rq because for the comparison with the surface only can be done with these two parameters.

	Ra	Rq	Radius	F	hc	Vibration
Footprint 13	3,8468	4,9051	100	153	0,100	Y
Footprint 2	4,0806	4,9482	80	153	0,1	N
Footprint 4	4,7605	5,9672	80	153	0,1	Y
Footprint 8	6,0787	7,6165	80	153	0,02	Y
Footprint 6	6,2975	7,4111	80	153	0,02	N
Footprint 1	7,4638	8,4768	80	180	0,100	N
Footprint 16	8,4588	9,9961	100	180	0,1	N
Footprint 18	8,568	9,8569	100	180	0,02	Y
Footprint 17	9,9092	11,653	100	153	0,020	Y
Footprint 15	10,046	11,902	100	153	0,100	N
Footprint 5	11,038	13,283	80	180	0,020	N
Footprint 14	12,554	14,285	100	180	0,1	Y
Footprint 11	12,734	15,002	90	129	0,060	Y
Footprint 19	12,972	14,958	100	153	0,020	N
Footprint 20	13,317	15,208	100	180	0,02	N
Footprint 9	13,37	15,716	90	129	0,060	N
Footprint 12	14,349	16,592	90	129	0,06	Y
Footprint 7	14,42	16,132	80	180	0,020	Y
Footprint 10	14,72	16,654	90	129	0,06	N
Footprint 3	16,313	18,645	80	180	0,100	Y

Table 20. Profile results by optical rugosimeter in order from best Ra to worst with its parameters associated measured by the SPIP CLASSIC

Following it will proceed the analysis of the ISO normative measures:

	Contact		Optic	
	Ra	Rq	Ra	Rq
Footprint 1	2,832	3,424	7,401	9,476
Footprint 2	1,303	1,599	1,27	1,653
Footprint 3	1,593	1,924	1,531	1,836
Footprint 4	1,423	1,792	5,613	8,753
Footprint 5	1,726	2,038	2,219	2,667
Footprint 6	1,365	1,69	3,002	5,932
Footprint 7	2,25	2,836	2,064	2,854
Footprint 8	1,282	1,541	1,329	1,609
Footprint 9	1,488	1,876	1,576	1,888
Footprint 10	1,426	1,788	1,093	1,402
Footprint 11	1,403	1,789	1,381	1,665
Footprint 12	1,294	1,608	1,078	1,439
Footprint 13	1,629	1,966	1,662	2,684
Footprint 14	0,652	1,327	1,802	2,141
Footprint 15	1,748	2,143	1,281	1,587
Footprint 16	1,225	1,483	1,957	2,505
Footprint 17	1,853	2,315	1,334	1,579
Footprint 18	1,389	1,661	2,36	3,804
Footprint 19	1,621	1,968	1,42	1,82
Footprint 20	0,898	1,33	1,875	2,234

Table 21. Comparison by footprint

	Rq	Ra	Ra	Rq	
Footprint 12	1,439	1,078	0,652	1,327	Footprint 14
Footprint 10	1,402	1,093	0,898	1,330	Footprint 20
Footprint 2	1,653	1,27	1,225	1,483	Footprint 16
Footprint 15	1,587	1,281	1,282	1,541	Footprint 8
Footprint 8	1,609	1,329	1,294	1,608	Footprint 12
Footprint 17	1,579	1,334	1,303	1,599	Footprint 2
Footprint 11	1,665	1,381	1,365	1,690	Footprint 6
Footprint 19	1,82	1,42	1,389	1,661	Footprint 18
Footprint 3	1,836	1,531	1,403	1,789	Footprint 11
Footprint 9	1,888	1,576	1,423	1,792	Footprint 4
Footprint 13	2,684	1,662	1,426	1,788	Footprint 10
Footprint 14	2,141	1,802	1,488	1,876	Footprint 9
Footprint 20	2,234	1,875	1,593	1,924	Footprint 3
Footprint 16	2,505	1,957	1,621	1,968	Footprint 19
Footprint 7	2,854	2,064	1,629	1,966	Footprint 13
Footprint 5	2,667	2,219	1,726	2,038	Footprint 5
Footprint 18	3,804	2,36	1,748	2,143	Footprint 15
Footprint 6	5,932	3,002	1,853	2,315	Footprint 17
Footprint 4	8,753	5,613	2,250	2,836	Footprint 7
Footprint 1	9,476	7,401	2,832	3,424	Footprint 1

Table 22. Comparison by order.

Annex IV Blueprints